MONTHLY WEATHER REVIEW

VOLUME 82 NUMBER 7

JULY 1954

CONTENTS

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MONTHLY WEATHER REVIEW

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 11, 1952

DEPARTMENT OF COMMERCE
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MONTHLY WEATHER REVIEW

Editor, JAMES E. CASKEY, JR.

Volume 82
Number 7

JULY 1954

Closed September 15, 1954
Issued October 15, 1954

A GENERALIZED STUDY OF PRECIPITATION FORECASTING

PART 3: COMPUTATION OF PRECIPITATION RESULTING FROM VERTICAL VELOCITIES DEDUCED FROM VORTICITY CHANGES

G. O. COLLINS AND P. M. KUHN [1]

Short Range Forecast Development Section, U. S. Weather Bureau, Washington, D. C.

[Manuscript received June 18, 1954]

ABSTRACT

Vertical velocities are deduced from two successive geopotential fields by means of a simplified vorticity equation. These velocities are used in a model described in earlier papers in this series to compute contemporary precipitation. Charts comparing computed with observed precipitation are shown.

INTRODUCTION

The computation of vertical velocity is an essential part of the problem of forecasting precipitation. In the preliminary exploratory phase of this investigation [1, 2], a precipitation model was developed relating the amount of precipitation to the fields of moisture and vertical velocity. Vertical velocities were computed by integrating with height the horizontal divergence of observed winds determined by a triangulation technique suggested by Bellamy [3]. Although the vertical velocities obtained by this kinematic method showed skill in delineating the areas over which precipitation occurred, the method is limited to a contemporary computation of precipitation since "true" winds are needed and forecasting these is at least as difficult as forecasting precipitation itself. In an attempt to obtain vertical velocities from a single geopotential field, various winds were derived—geostrophic and gradient winds using contour spacing and curvature, and gradient winds computed from a cubic surface fitted to reported heights; the resulting horizontal divergence and vertical velocities calculated from these winds were found to give insufficient information for computing precipitation. However, if one considers two successive geopotential fields, it is possible to deduce vertical velocities from changes in the vorticity of the geostrophic wind. The purpose of the present investigation was to study the usefulness of such vertical velocities in predicting precipitation.

COMPUTATION OF VERTICAL VELOCITY

The idea of using the vorticity equation to compute vertical motion is not a new one and has been advanced by several authors. The development used in this study is very similar to that given by Eliassen and Hubert [4] and consequently will be discussed only briefly here.

Using pressure as the vertical coordinate, the vorticity equation may be written

$$\frac{\partial \eta}{\partial t} = -\mathbf{V}\cdot\nabla\eta - \omega\frac{\partial \eta}{\partial p} + \eta\frac{\partial \omega}{\partial p} \qquad (1)$$

where η denotes absolute vorticity (vertical component), $\mathbf{V}$ and ∇ are vectors in a constant pressure surface, p is pressure and ω is the individual rate of change of pressure $\left(=\frac{dp}{dt}\right)$. Frictional influences and the turning of the vortex lines are

[1] Present address: Department of Meteorology, University of Wisconsin, Madison, Wis.

neglected. Neglect of the latter probably causes serious errors in small highly baroclinic areas, for example, near strong frontal regions. However, including these terms would have added considerably to the already enormous computations and they are therefore omitted.

Dividing through by η^2 and rearranging, equation (1) may be written

$$\frac{\partial}{\partial p}\left(\frac{\omega}{\eta}\right)=\frac{\frac{\partial \eta}{\partial t}+\mathbf{V}\cdot\nabla\eta}{\eta^2} \tag{2}$$

This can be integrated to obtain

$$\left(\frac{\omega}{\eta}\right)_{p=p_1}=\left(\frac{\omega}{\eta}\right)_{p=p_0}+\int_{p_0}^{p_1}\frac{\frac{\partial \eta}{\partial t}+\mathbf{V}\cdot\nabla\eta}{\eta^2}dp \tag{3}$$

Evaluating the integral by the trapezoidal rule gives

$$\left(\frac{\omega}{\eta}\right)_{p=p_1}=\left(\frac{\omega}{\eta}\right)_{p=p_0}+\frac{1}{2}\left[\left(\frac{\frac{\partial \eta}{\partial t}+\mathbf{V}\cdot\nabla\eta}{\eta^2}\right)_{p=p_1}+\left(\frac{\frac{\partial \eta}{\partial t}+\mathbf{V}\cdot\nabla\eta}{\eta^2}\right)_{p=p_0}\right](p_1-p_0) \tag{3a}$$

Thus, given the vorticity and its changes at various levels and ω at the lower boundary, we can obtain $\frac{\omega}{\eta}$, and thus ω, at any level. For instance, at 850 mb.,

$$\left(\frac{\omega}{\eta}\right)_{850}=\left(\frac{\omega}{\eta}\right)_{1000}-\frac{1}{2}\left[\left(\frac{\frac{\partial \eta}{\partial t}+\mathbf{V}\cdot\nabla\eta}{\eta^2}\right)_{1000}+\left(\frac{\frac{\partial \eta}{\partial t}+\mathbf{V}\cdot\nabla\eta}{\eta^2}\right)_{850}\right]150 \tag{3b}$$

Using the hydrostatic equation, an approximate relationship can be derived between ω and w, the vertical velocity, using height as a vertical coordinate.

$$w=\frac{dz}{dt}\approx-\frac{\omega}{\rho g} \tag{4}$$

where ρ is the density of air and g is the acceleration of gravity.

Vorticity was computed for four levels (1,000, 850, 700 and 500 mb.) by a graphical procedure described by Fjørtoft [5]. Briefly, the method is to shift the contour field a specified distance east and west and north and south and obtain a space-averaged contour field. Subtracting from this the original contour field gives a quantity proportional to the relative vorticity. Absolute vorticity, or more precisely a parameter roughly proportional to the absolute vorticity, is obtained by graphically adding in a term which is a function of latitude. The mesh length used was six degrees of latitude as suggested by Fjørtoft. Various other mesh lengths were tried but this one gave what was considered to be the best degree of smoothing.

Successive charts, 12 hours apart, were subtracted to obtain $\frac{\partial \eta}{\partial t}$. Since the quantity obtained was a 12-hour average rather than an instantaneous value, all other parameters were averaged over the 12-hour period. The advection of vorticity, $\mathbf{V}\cdot\nabla\eta$, was computed graphically and the values at the beginning and end of the 12-hour period were averaged.

These quantities were combined by graphical methods and integrated vertically as indicated by equation (3) to obtain vertical velocities at 850, 700, and 500 mb. These velocities were considered to be the mean for the 12-hour period. A typical set of isanabats for 0300–1500 GMT, January 3, 1953, is shown in figure 1B, C, D. The associated sea level chart for 0630 GMT is shown in figure 1A.

Two sets of computations were made, one by assuming that $\omega=0$ at 1,000 mb. which was assumed to be the surface pressure, and the other by introducing at the ground a topographically induced vertical motion. This was computed assuming

$$w_{1000}=\mathbf{V}\cdot\nabla h \tag{5}$$

where h is the height of the ground. Surface contours used were from a chart of smoothed broad-scale topography by Smagorinsky [6]. For the "advecting" wind, both observed "gradient level" winds and geostrophic winds at 850 mb. were used with substantially similar results. Topographic vertical velocities obtained at the beginning and end of a 12-hour period were averaged to give a value consistent with the average velocities deduced from equation (3). Figure 2 shows the vertical velocity fields computed for 0300–1500 GMT, January 3, 1953, taking into account the forced orographic ascent. This can be compared with figure 1, the results assuming a vertical velocity of zero at the surface. The flow was approximately from the northwest resulting in upward velocities on the western slopes of the Appalachians and downward velocities toward the east (fig. 2A). The effect of topography shows up most pronouncedly at the 850-mb. level where the isanabats are distorted north and southward along the mountain ridges.

COMPUTATION OF PRECIPITATION

Given the fields of vertical velocity and moisture, the amount of precipitation that will result in a 12-hour period was shown by Thompson and Collins [1] to be

$$P=\Sigma\{I[w-0.28(T-T_d)]\Delta z\} \tag{6}$$

where the atmosphere is divided into a number of layers and P, the 12-hour amount of precipitation, is the summation of the contributions of the various layers. For this present study three layers, approximately centered at 850, 700, and 500 mb. were used. In equation (6) I is a function of pressure and temperature, $(T-T_d)$ is the dewpoint depression in degrees Celsius and Δz is the thickness of the layer. As described by Kuhn [2], this equa-

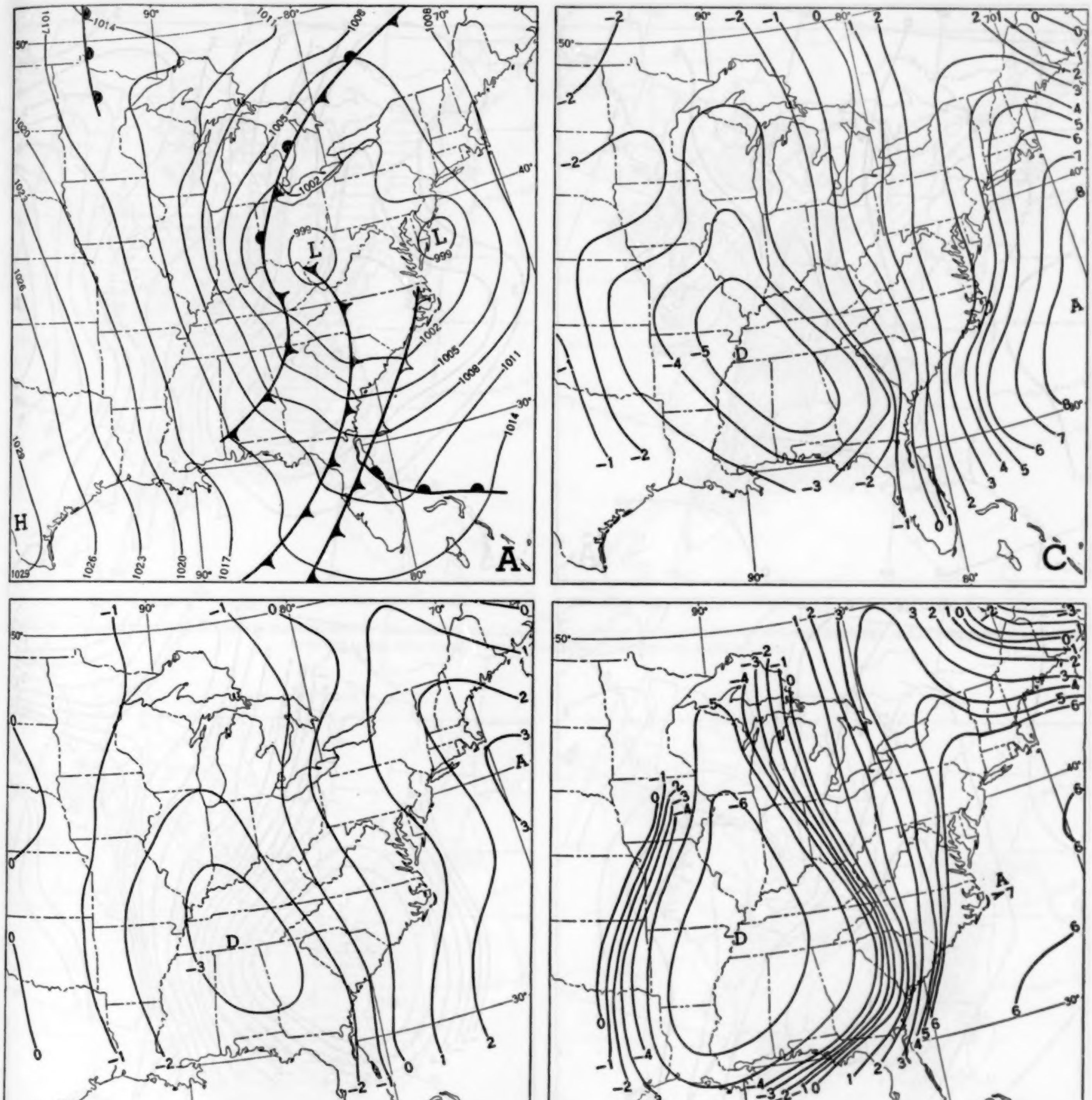

FIGURE 1.—(A) Surface chart, 0630 GMT, January 3, 1953. (B, C, D) Mean vertical velocity (cm. sec.$^{-1}$), 0300–1500 GMT, January 3, 1953, for 850, 700, and 500 mb., respectively. Positive values indicate ascent.

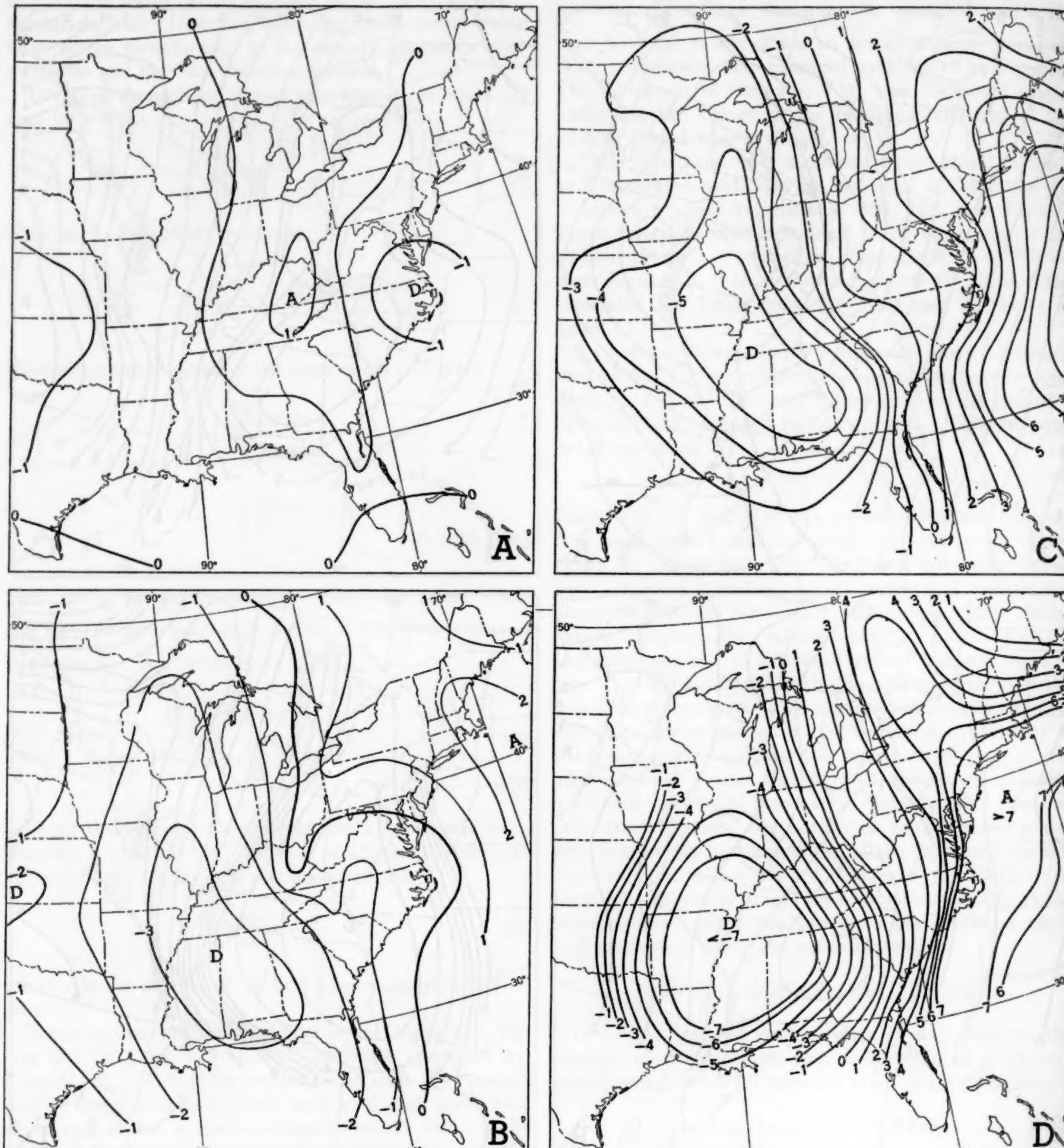

FIGURE 2.—Mean vertical velocity including topographic effects, 0300–1500 GMT, January 3, 1953 for (A) 1,000 mb., (B) 850 mb., (C) 700 mb., (D) 500 mb. Positive values indicate ascent.

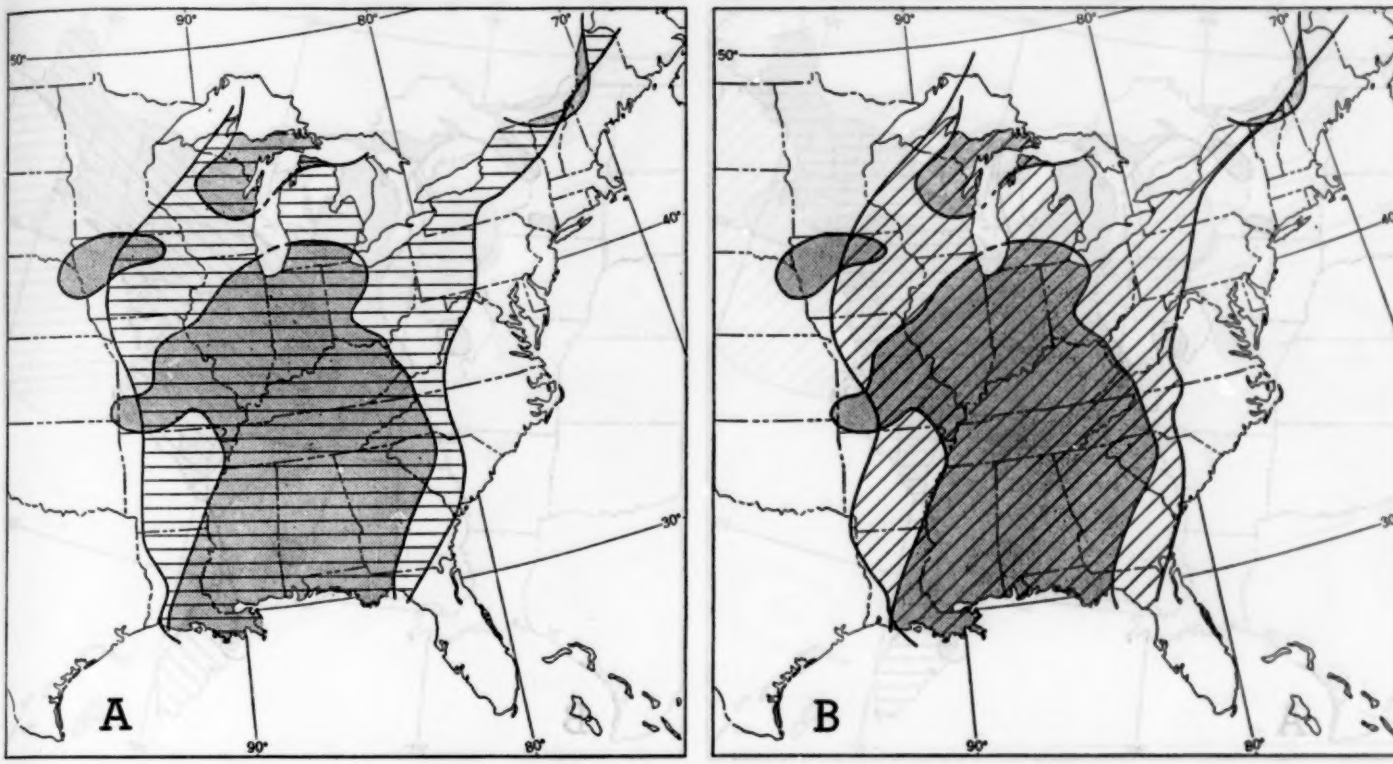

FIGURE 3.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 0300–1500 GMT, January 2, 1953.

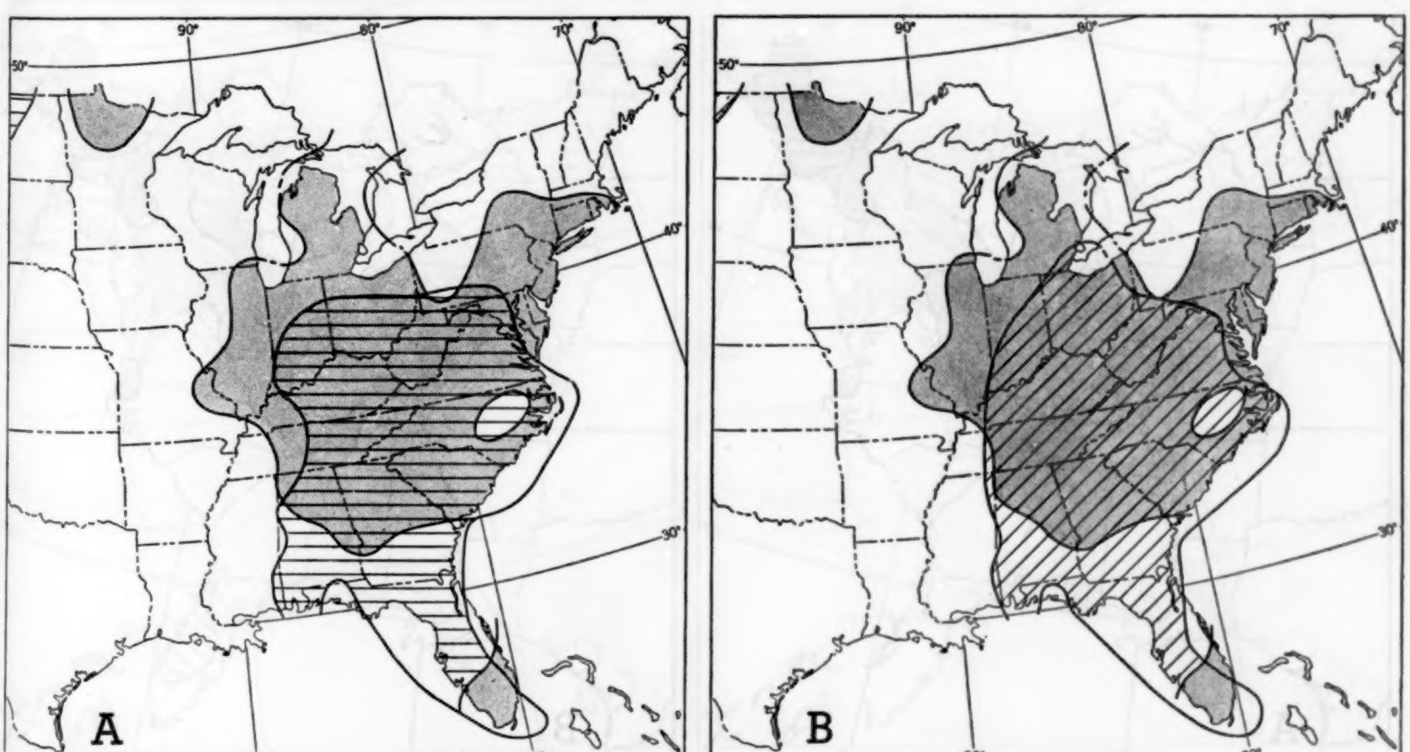

FIGURE 4.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 1500 GMT, January 2–0300 GMT, January 3, 1953.

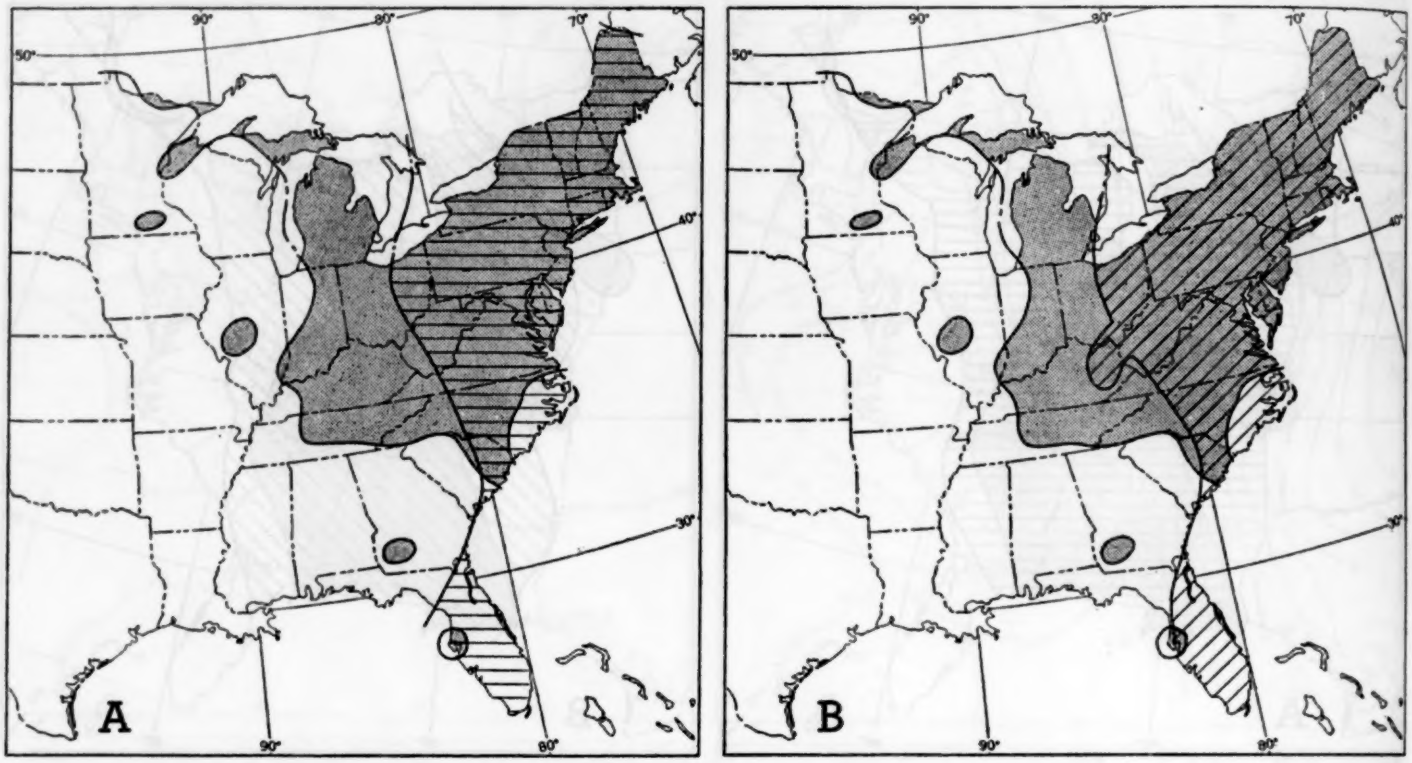

FIGURE 5.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 0300–1500 GMT, January 3, 1953.

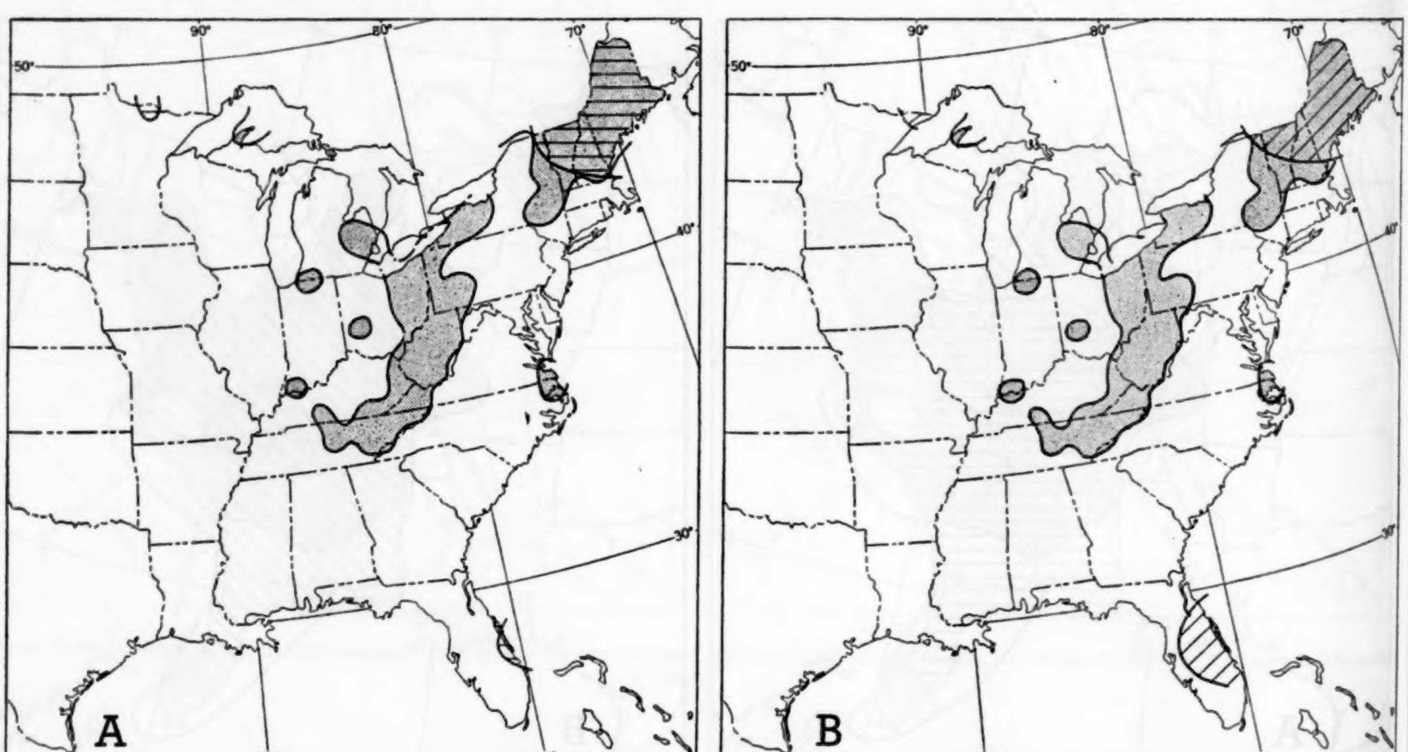

FIGURE 6.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 1500 GMT January 3–0300 GMT January 4, 1953.

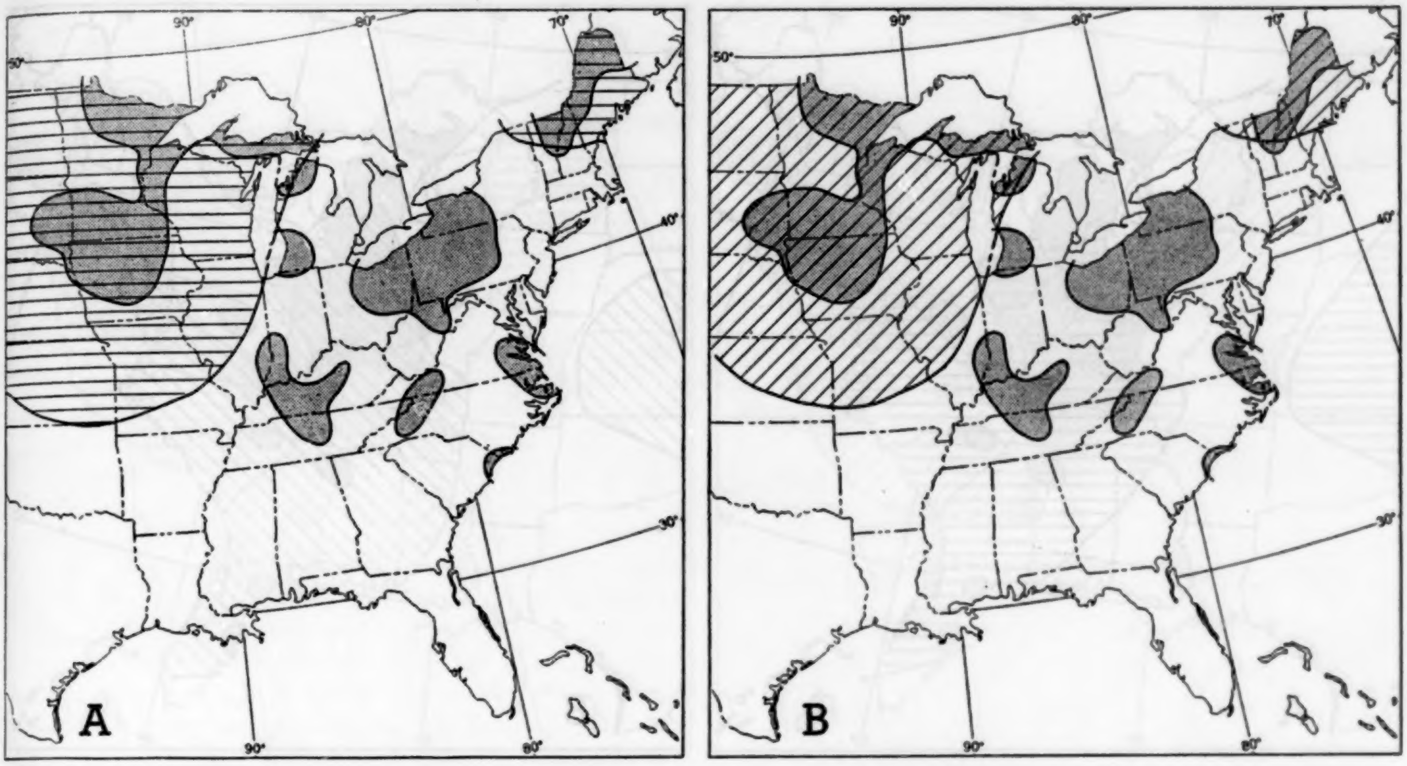

FIGURE 7.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 0300–1500 GMT, January 4, 1953.

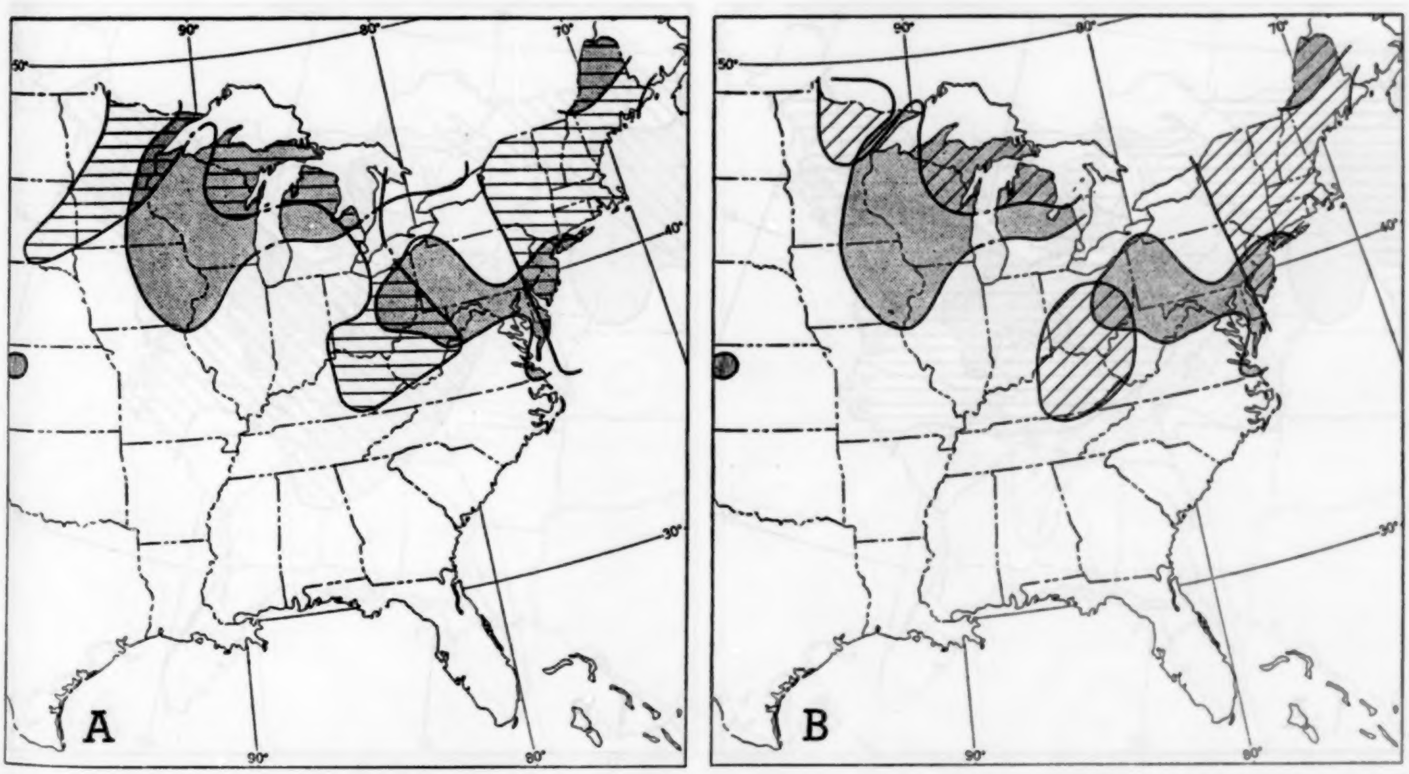

FIGURE 8.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 1800 GMT January 4–0300 GMT January 5, 1953.

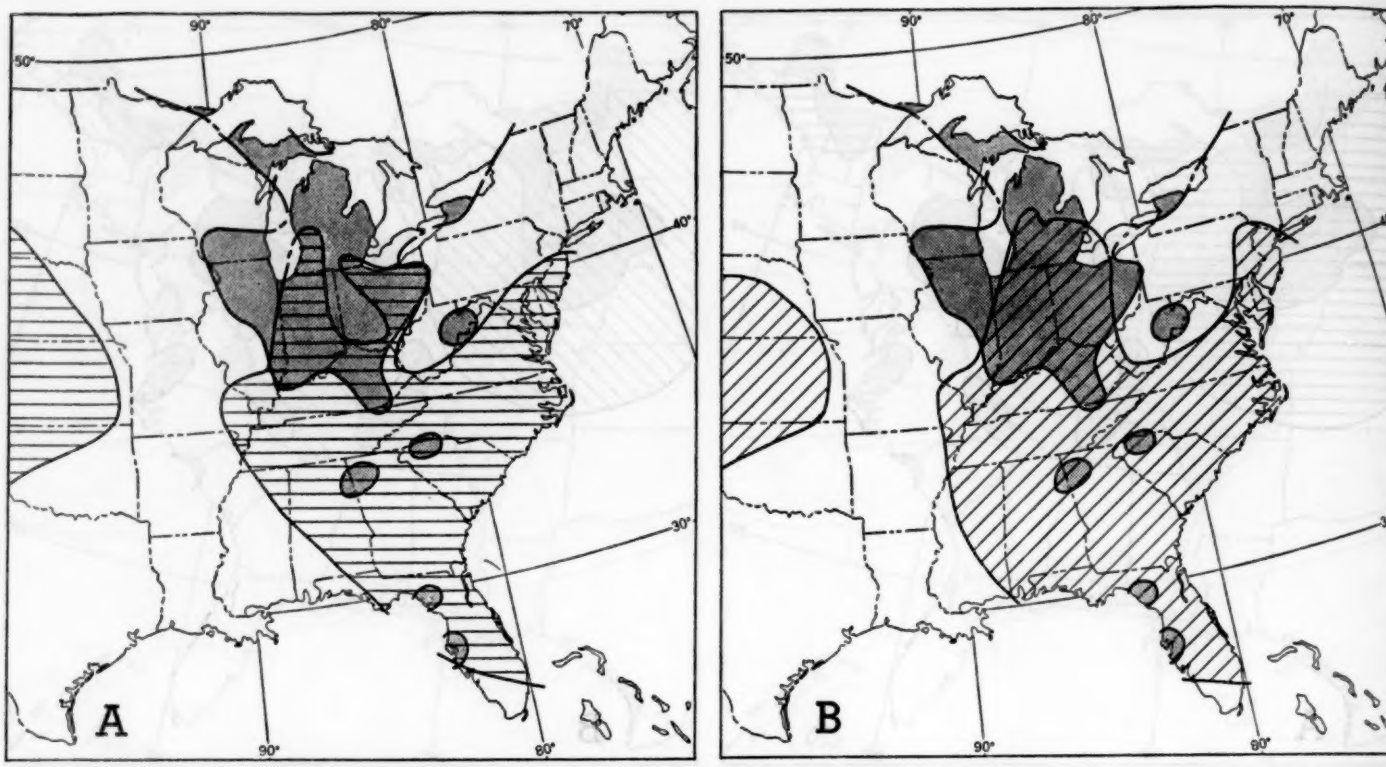

FIGURE 9.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 0300-1500 GMT, January 5, 1953.

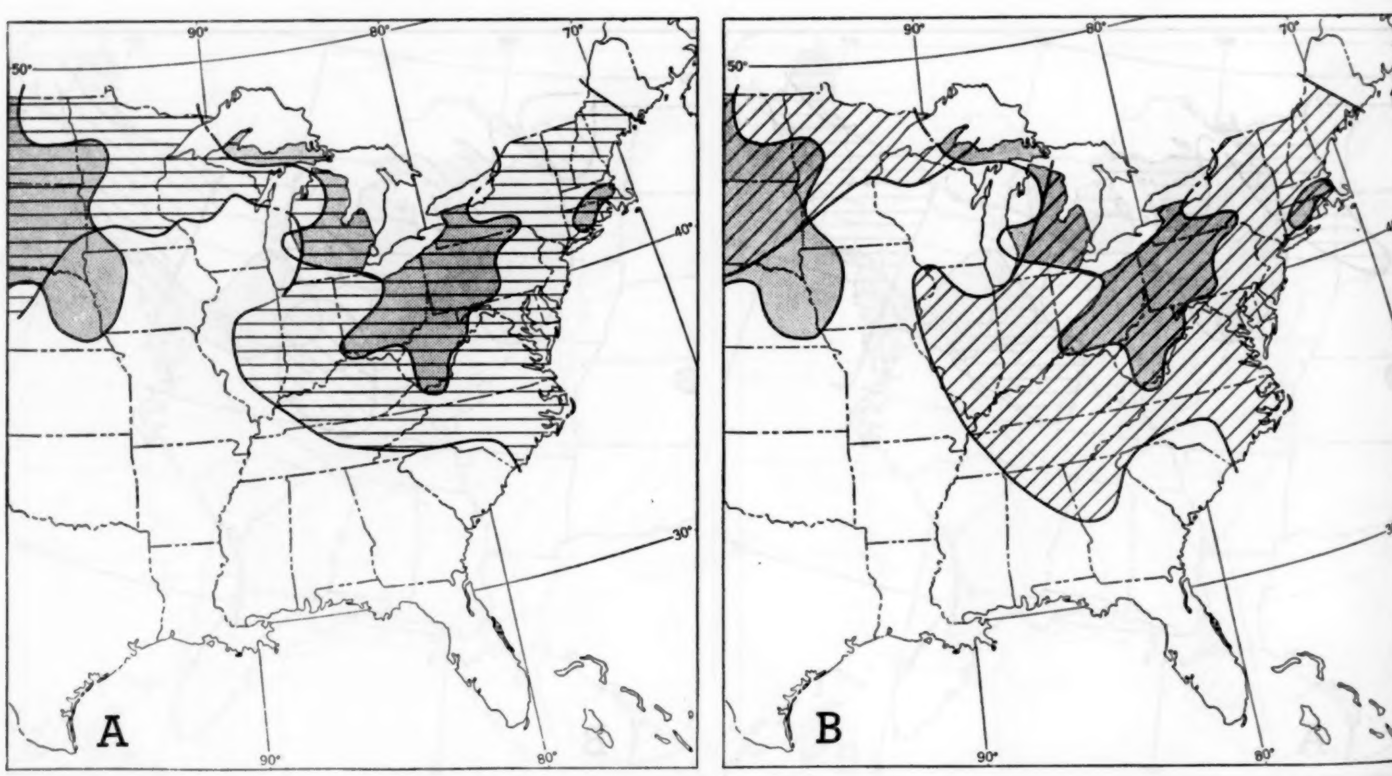

FIGURE 10.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 1500 GMT, January 5-0300 GMT, January 6, 1953.

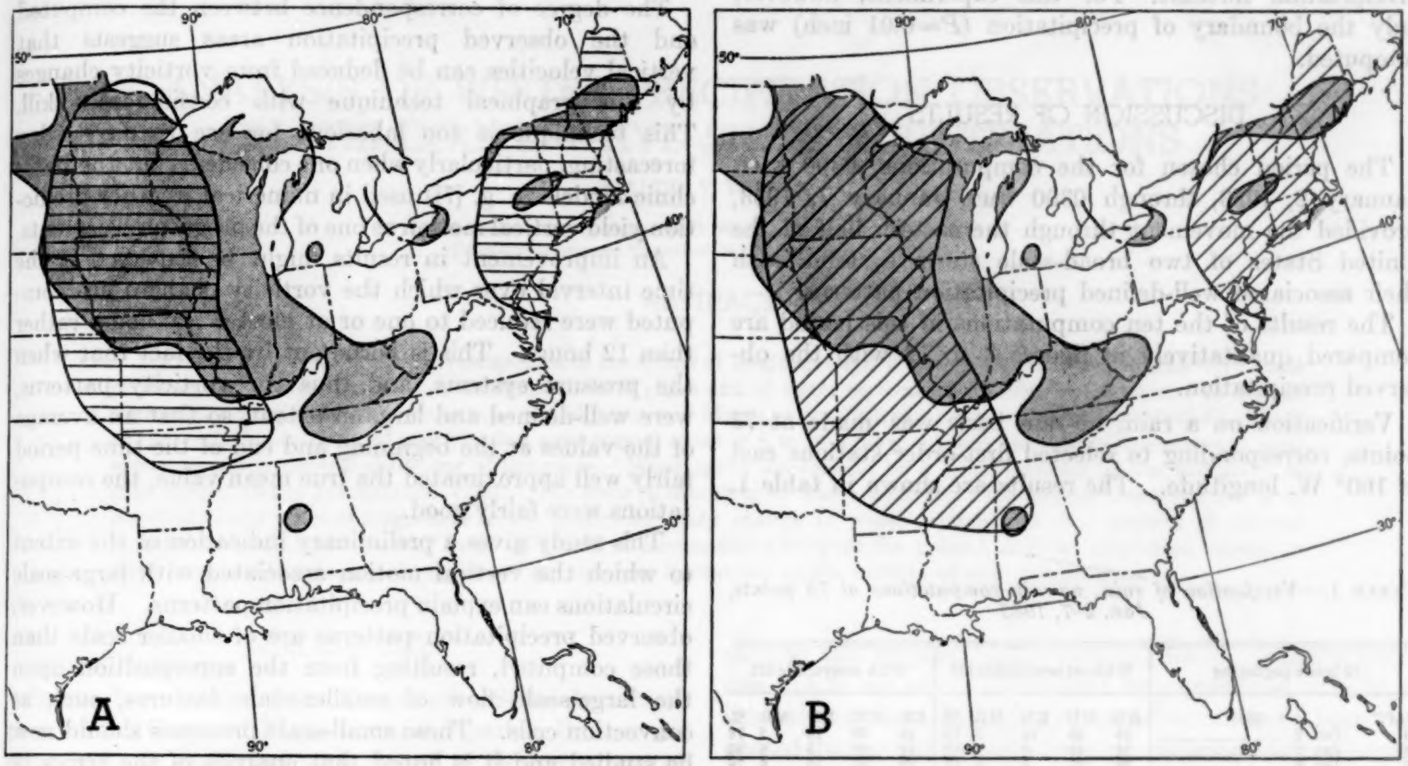

FIGURE 11.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 0300-1500 GMT, January 6, 1953.

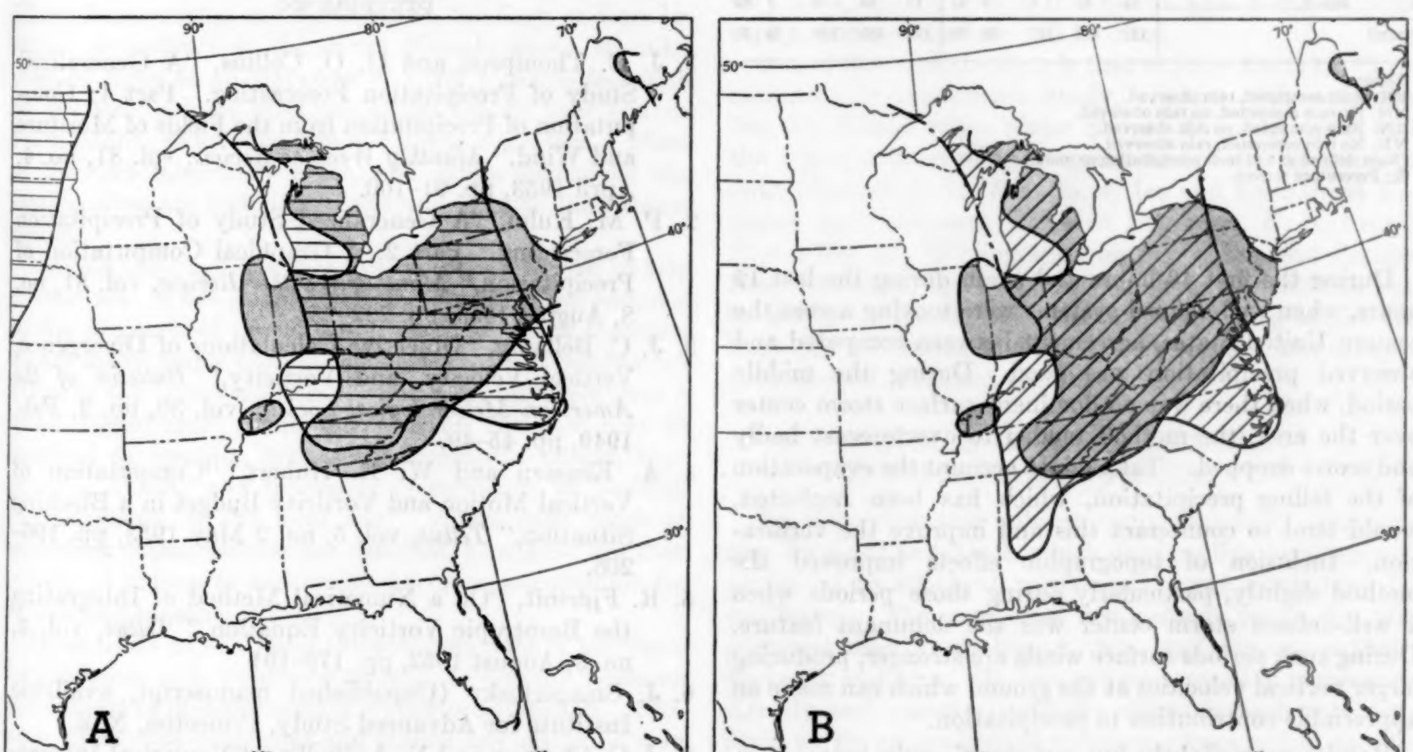

FIGURE 12.—Observed precipitation (shaded) superimposed on (A) computed precipitation not including topographic effects (horizontal hatching), and (B) computed precipitation including topographic effects (diagonal hatching). 1500 GMT, January 6-0300 GMT, January 7, 1953.

tion can be evaluated graphically to give a quantitative precipitation forecast. For this experiment, however, only the boundary of precipitation ($P=0.01$ inch) was computed.

DISCUSSION OF RESULTS

The period chosen for the computations, 0300 GMT, January 2, 1953, through 0300 GMT, January 7, 1953, provided the movement through the eastern half of the United States of two broad-scale storm systems with their associated well-defined precipitation patterns.

The results of the ten computations in this period are compared qualitatively in figures 3 to 12 with the observed precipitation.

Verification on a rain, no-rain basis was made at 73 points, corresponding to selected first-order stations east of 100° W. longitude. The results are shown in table 1.

TABLE 1.—*Verification of rain, no-rain computations at 73 points, Jan. 2–7, 1953*

12 hours beginning		Without orographic lift					With orographic lift				
GMT	1953	RR	NN	RN	NR	%	RR	NN	RN	NR	%
03	Jan. 2	18	39	14	2	78	18	39	14	2	78
15	Jan. 2	14	45	6	8	81	14	46	5	8	82
03	Jan. 3	19	37	8	9	77	22	35	10	6	78
15	Jan. 3	8	55	2	8	86	8	56	1	8	88
03	Jan. 4	9	41	17	6	69	9	42	16	6	70
15	Jan. 4	9	46	13	5	75	9	49	10	5	80
03	Jan. 5	6	48	15	4	74	7	45	18	3	71
15	Jan. 5	13	38	21	1	70	13	36	23	1	67
03	Jan. 6	13	38	13	9	70	13	36	15	9	67
15	Jan. 6	13	46	8	6	81	12	48	6	7	82
Overall		122	433	117	58	76	125	432	118	55	76

Notes:
RR: Rain computed, rain observed.
NN: No rain computed, no rain observed.
RN: Rain computed, no rain observed.
NR: No rain computed, rain observed.
(Rain defined as 0.01 inch precipitation or more.)
%: Percentage correct.

During the first 48 hours and again during the last 12 hours, when well-defined systems were moving across the eastern United States, agreement between computed and observed precipitation was good. During the middle period, when there was no dominant surface storm center over the area, the method tended to overforecast badly and scores dropped. Taking into account the evaporation of the falling precipitation, which has been neglected, would tend to counteract this and improve the verification. Inclusion of topographic effects improved the method slightly, particularly during those periods when a well-defined storm center was the dominant feature. During such periods surface winds are stronger, producing larger vertical velocities at the ground which can make an appreciable contribution to precipitation.

Results were slightly but not significantly better than those of [2], which used the horizontal divergence of observed winds, smoothed horizontally, to compute vertical velocity.

CONCLUSIONS

The degree of correspondence between the computed and the observed precipitation areas suggests that vertical velocities can be deduced from vorticity changes by this graphical technique with considerable skill. This technique is too laborious for use in day-to-day forecasting, particularly when one considers that the baroclinic models (e. g. [7]) used in numerical weather prediction yield vertical motion as one of the prognostic elements.

An improvement in results might be expected if the time interval over which the vorticity changes are computed were reduced to one or at most a few hours rather than 12 hours. This is borne out by the fact that when the pressure systems, and thus the vorticity patterns, were well-defined and large in extent, so that an average of the values at the beginning and end of the time period fairly well approximated the true mean value, the computations were fairly good.

This study gives a preliminary indication of the extent to which the vertical motion associated with large-scale circulations can explain precipitation patterns. However, observed precipitation patterns are of smaller scale than those computed, resulting from the superposition upon the large-scale flow of smaller-scale features, such as convection cells. These small-scale processes should now be studied and it is hoped that analysis of the errors in these ten cases will yield information on the relationships between the large-scale flow and the small-scale phenomena.

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ANALYSIS OF WINTER PRECIPITATION OBSERVATIONS IN THE COOPERATIVE SNOW INVESTIGATIONS

WALTER T. WILSON

Division of Hydrologic Services, U. S. Weather Bureau, Washington, D. C.

[Manuscript received November 24, 1953; revised July 9, 1954]

ABSTRACT

In the Cooperative Snow Investigations of the Corps of Engineers and Weather Bureau, observations were made of precipitation measurements in different kinds of gages and of water equivalent of snow on the ground at a great variety of station sites in the mountains of California and Montana for the five winter seasons ending 1950–51. Much of the variation in catch of precipitation over rugged areas of 4 to 20 square miles is ascribed to variations in local exposure and in natural sheltering of the gages. Wind speed appears to be a good measure of the adequacy of gage shelter and of precipitation catch. The error in sampling of water equivalent for average snow courses is of about the same order of magnitude as the maximum daily change in water equivalent. For seasons of several months' length, observations of gage catch and of accumulated snow on the ground, each at good sites, appear to have comparable precision though there are inherent limitations in the validity of such comparisons.

INTRODUCTION

Some observations of the Cooperative Snow Investigations of the Corps of Engineers and Weather Bureau are organized and displayed with regard to measurements of winter precipitation in mountainous terrain. The data have been published in the *Hydrometeorological Logs* of the Central Sierra and Upper Columbia Snow Laboratories. These Laboratories are described in the Logs and are located respectively in the Sierra Nevada about 40 miles west of Reno at an elevation of 7,000 to 9,000 feet, and on the west side of the Continental Divide near Glacier Park, Mont., at an elevation of 5,000 to 8,000 feet. Maps of the two laboratory areas, and tables describing the station sites are included in the appendix to the present report.

Among the questions that this report is intended to help answer are: What quantitative measures can be assigned to the precision of precipitation and snow pack measurements made under normal but observed field conditions? What is the true variation of winter precipitation over a small rugged area? How much of this variation may be ascribed to weather, large-scale orographic effects, type of gage, quality and frequency of servicing, or physical characteristics of the local site? Where gage catch or snowpack measurements are deficient, how good are they merely as indices to accumulated winter precipitation for forecasting seasonal runoff?

In addition to analyzing the observed data of the Snow Laboratories it is necessary to refer to current views on the subject of measurement of winter precipitation. Current views vary somewhat and almost any plausible view on any issue can be supported by a formidable array of references to earlier work. Context is extremely important to this subject, in the strictest sense. Results from one site or set of conditions can be generalized only to a limited degree. Hundreds of experiments have been repeated during the last century with differing environments all over the world. An evaluation of the literature would transcend the scope of this report. Rather than attempting to support each statement not based on Snow Laboratory data, and burdening this report with a long bibliography, two publications will be cited.

One of these publications is that of John Kurtyka, "Precipitation Measurements Study," *Report of Investigation* No. 20, Illinois State Water Survey Division, 1953, and the other, a continuing program under the direction of John Sherrod, is *SIPRE* (Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U. S. Army) *Report* No. 12, "Bibliography on Snow, Ice, and Permafrost," prepared by the Library of Congress, volumes 1 to 6, the latter dated July 1954. These bibliographies are both well annotated and indexed by subject, and contain thousands of pertinent citations.

SOURCES OF AREAL VARIATION IN PRECIPITATION MEASUREMENT

To help view this subject comprehensively reference may be made to table 1, which displays five fundamental categories to which all variation in gage catch may be attributed. The categories are defined partly by the processes used in analyzing them, and are not entirely mutually exclusive. It does not seem possible to measure directly and quantitatively the effects in each category, such as by an analysis of variance. Orographic parameters, for example, are ordinarily defined by analysis of mean seasonal or mean annual precipitation, whereas

TABLE 1.—*Categories of variation in precipitation catch*

	Category	Expressed in terms of:	Examples	Scale	Operates on:	Method of control for estimating areal precipitation
I	Storm experience	Storm occurrence	Location with respect to storm center.	Miles	Storm paths and processes	Areal sampling.
II	Physiography	Orographic parameters	Position on, or distance to large mountains.	Miles	Condensation processes and falling precipitation.	Stratified sampling of parameters.
III	Environment	Double-mass analysis	Distance from small ridge	100's of feet	Falling precipitation	Minimize error by site selection.
IV	Site	Rules of thumb	Height of nearby trees	Feet	Falling precipitation	Minimize error by selection or modification of site.
V	Gage	Gage characteristics	Depth and diameter of funnel.	Inches	Falling precipitation	Minimize error by choice or design of gage and its components.

double-mass analysis requires annual or seasonal totals. The general practice is to standardize the categories near the bottom of the table and to stay within reasonable class limits of the other categories. For example, before orographic parameters can be evaluated the data should first be subjected to double-mass analysis and should be selected from a homogeneous climatic region. How homogeneous the region must be, and with respect to what feature of precipitation regime, is a matter to be defined operationally and with respect to a particular application.

The storm experience category could logically be broken down into detail that would recognize not only storm paths and position of a gage within a storm, but also type of storm (warm front, cold front, orographic, convective, etc.). Further consideration leads to recognition of the seasonal variation in the occurrence and importance of precipitation associated with the respective storm types. These meteorological parameters might lead to a more rational procedure for identifying and defining zones of environment in category II.

Double-mass analysis is useful for identifying changes in the last three categories, and in providing measures of their net effect, but it has limited analytical value. Further study is needed for evaluating category IV, and breaking it down into rational elements. There seems to be a need for objective rules in appraising gage sites. A corollary is the need for definitive criteria for deciding, when a gage is to be moved, whether to change its station designation or to regard the new record as a continuation of the old one. Attention and work have been lavished (in category V) on gage design to a degree that may long ago have reached the point of diminishing returns.

Practical justification for further study of the influences on variation of precipitation catch over an area comes from the needs for improving forecasts of streamflow, design of structures, and other applications. It may be wondered what proportion of the residual error in a forecasting relationship based on average areal precipitation may be ascribed to each of the following sources: imperfect form of functional relationship, inadequate consideration of additional variables, deficient period of record, and errors in sampling precipitation over an area. The first two sources have been subjected to intensive and extensive trial and error and much ingenuity; the third source is largely a matter of time. The fourth source, quality of basic data, presents an excellent opportunity for fruitful effort at this time. The importance of improving basic data, the significant influence of site characteristics on basic data, and the fact that there has been no conclusive evaluation of site characteristics were among the considerations that led to undertaking and reporting on this subject. The results of the analyses are presented mostly by means of scatter diagrams.

VARIATION AT A SINGLE STATION

Figures 1–4 show how much variation exists within the confines of a single station—that is over distances of a few feet rather than miles. Figure 1 shows daily values of precipitation at Station 1B plotted against those at Station 1C, Central Sierra Snow Laboratory, 1947–48 winter season. The gage at Station 1B is a Friez and that at 1C a Stevens recorder; they are 20 feet apart and on towers. Omitting the data concentrated near the origin, the correlation coefficient is about 0.98, and slight bias is evidenced by the central tendency being above the 45° line passing through the origin. The scatter shows differences due to the different positions of the gages in the forest clearing, differences in the gage shape and mechanism, differences in reading the charts, capping of one or the other gage at times (errors due to capping may affect timing as well as total storm catch), missing record, different quality of servicing from time to time, and additional influences that might be suggested. It would be difficult to separate and measure the proportion of total variation ascribable to each influence. The standard error of estimate is about 0.14 inch, which may be regarded as a good measure of the quality of daily observations of winter precipitation at well-attended gages of this kind.

Figure 2 shows the water equivalent of snowpack on successive days during the 1948–49 season at points 1 and 2 in the Station 1 sampling site at Upper Columbia Snow Laboratory. The correlation here is about 0.98, with a standard error of estimate of about one inch. It is the practice of snow surveyors to report water equivalent to the closest half inch, which seems reasonable in view of this scatter. These two points are about 20 ft. apart, and

"drift" about some during the season to avoid old sampling holes. In order to avoid old sampling holes in a program of daily observations, a fairly large sampling area is necessary. The site used was chosen on the basis of its proximity to other observations near station 1 and its uniform and level terrain, and it was posted to prevent disturbance of the snow. Care was used in programming the observations so as to minimize the confounding of variation of water equivalent from day to day with its variation from place to place, and it is believed that the degree of this confounding is comparable with that inherent in routine snow surveying.

Efforts to separate some of the effects of variation in snowpack water equivalent from time to time among points at the same station include a comparison of variation in snow depth with the variation of water equivalent. In general the coefficient of variation of water equivalent exceeds that of depth by about 50 percent, indicating that considerable variation in sampling water equivalent cannot be ascribed to variation in snow depth.

Most of the snow courses at the Cooperative Snow Investigations Laboratories had from 5 to 10 points, as indicated in the Logs, and their standard error of estimate averaged about 2 inches water equivalent. Attempts to isolate some of the sources of error in water equivalent were made by studying data from the radioactive gage, where the snow is not disturbed, but the variation at this one point was about as great as at an average single point in a snow course. The radioactive gage is described briefly and literature cited in the 1949–50 Hydrometeorological Log of the Central Sierra Snow Laboratory. Its essential feature is the observing of water equivalent without disturbing the snowpack in any way. The gage operates by absorption by the snow mass of gamma rays emitted from a source at the ground surface and observed by a Geiger-Müller tube suspended over the snow above the radiation source. The greater the water equivalent the more absorption and the smaller the gamma count.

Figure 3 shows, for the same period and points as figure 2, the daily changes in snowpack water equivalent. The dispersion indicates a standard error of estimate of about 0.8 inch. It is evident from the scatter that the error is of the same order of magnitude as the change from day to day—a noteworthy fact in considering attempts to estimate daily snow melt by daily changes in water equivalent of deep snow. The points in the 2d and 4th quadrants mark occasions of increase in observed water equivalent at one point and decrease at the other.

The 0.8 inch standard error of figure 3 is not inconsistent with the value of 2.0 given earlier as the general average for the Laboratories. Most of the sites are more rugged than the one where daily samples were taken, and many of the stations were deliberately located to sample terrain features that are usually avoided in routine snow surveying. There was a marked trend of diminishing standard error from year to year because of progressive improvement in marking of the points where individual cores were

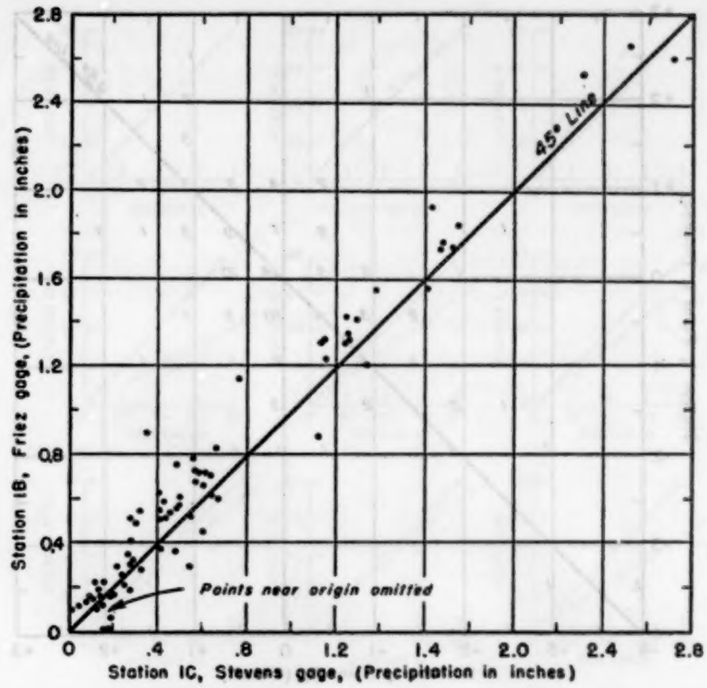


FIGURE 1.—Correlation of daily precipitation at two shielded recording gages 20 feet apart, Central Sierra Snow Laboratory, 1947–48 season.

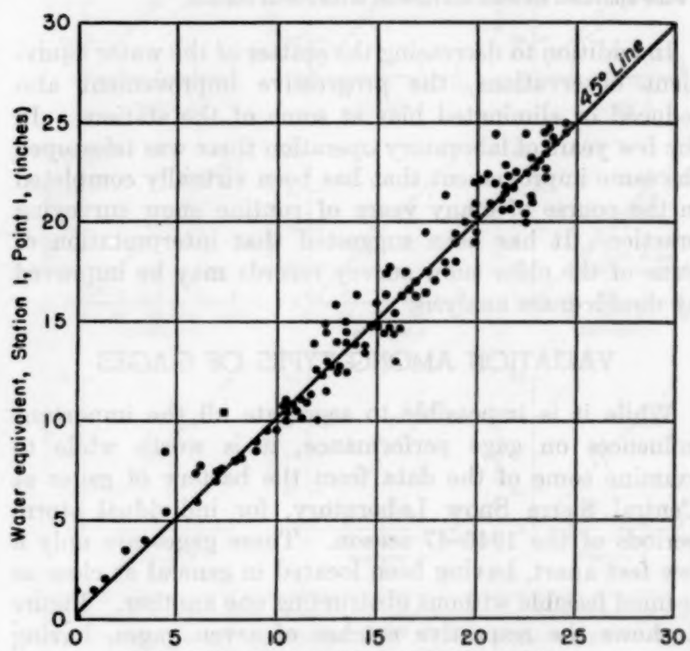


FIGURE 2.—Correlation of daily values of snowpack water equivalent at points 20 feet apart, station 1, Upper Columbia Snow Laboratory, 1948–49.

taken, removing of obstructions such as rocks, smoothing of ground irregularities, and better technique in taking and evaluating individual cores. Decisions whether to accept or reject cores were made objectively on the basis of such criteria as consistent snowpack density throughout the sampling area and high ratios of core length to snow depth. Some snow sampling points were moved after evaluating the effects of drifting or scouring.

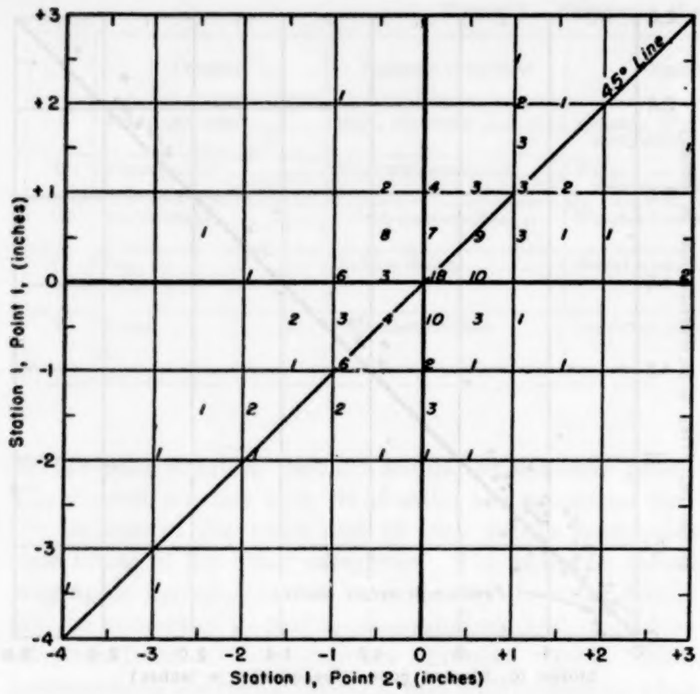


Figure 3.—Correlation of daily changes in snowpack water equivalent at points 20 feet apart, station 1, Upper Columbia Snow Laboratory, 1948–49. Numbers indicate the number of observations that might be plotted at each intersection. Observations of water equivalent are made and reported to the nearest half inch.

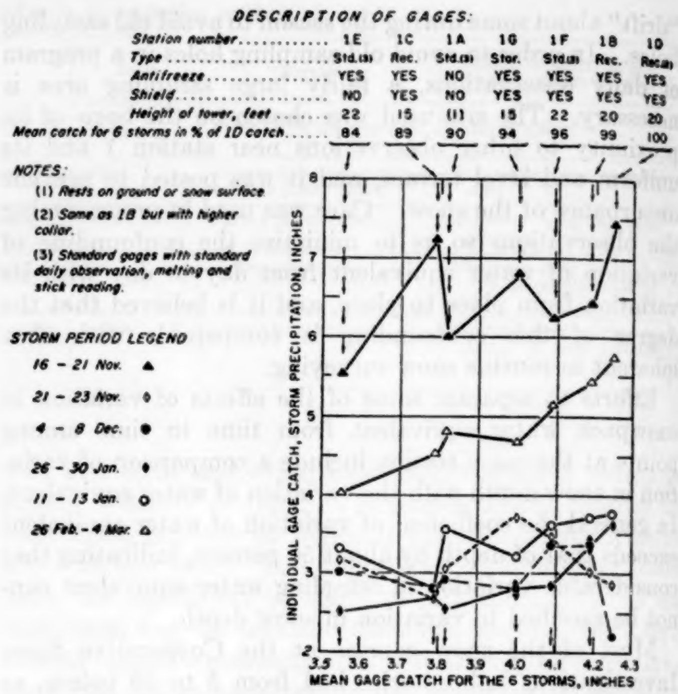


Figure 4.—Comparison of catch of seven different types of gage and gage installations, Central Sierra Snow Laboratory, 1946–47.

In addition to decreasing the scatter of the water equivalent observations, the progressive improvement also reduced or eliminated bias at some of the stations. In the few years of laboratory operation there was telescoped the same improvement that has been virtually completed in the course of many years of routine snow surveying practice. It has been suggested that interpretation of some of the older snow survey records may be improved by double-mass analysis.

VARIATION AMONG TYPES OF GAGES

While it is impossible to segregate all the important influences on gage performance, it is worth while to examine some of the data from the battery of gages at Central Sierra Snow Laboratory, for individual storm periods of the 1946–47 season. These gages are only a few feet apart, having been located in general as close as seemed feasible without obstructing one another. Figure 4 shows the respective catches of seven gages, having different combinations of shielding, type of gage, etc. As indicated earlier in comparing gages 1B and 1C, the position within the clearing might account for some of the variation. Complete replication would have been impossible. Noteworthy conclusions are the variation in ratio of catch of paired gages from storm to storm, and the magnitude of their mean ratios to the catch of the gage having the greatest catch. The variation of ratio of catch is illustrated in the comparison of gages 1B and 1C where, in the first November storm, 1C caught 7.2 inches whereas 1B caught 6.5 inches. In the March storm, by contrast, 1C caught 4.5 inches and 1B, 5.4 inches. On the average, the gage catching the least caught 84 percent as much as the gage catching the most for these six storm periods. Many comparisons can be made, and only a few will be cited. The main difference between 1A and 1E, both standard "cans", is that 1A was on the ground or snow surface and had no charge, whereas 1E was on a 22-foot tower and was charged with antifreeze. With daily attendance the charge would not be an important factor. It might be concluded that even with the light wind in this clearing the tower exposure was an appreciable detriment, particularly when the snow was shallow. Gage 1F was different from 1E only in that 1F was shielded. Evidently the shield makes a difference, for this type of gage at this site, of 10 to 15 percent.

VARIATIONS FROM STATION TO STATION, BY SEASONS

Figure 5 shows for each of several gages the respective catches for the two seasons 1946–47 and 1947–48, October through March, Central Sierra Snow Laboratory. The stations are identified by number in the scatter diagram. The average relation shows the 1947–48 season had more precipitation than the 1946–47 season by about 10 percent. Some of the scatter is due to the fact that missing records made it necessary to estimate portions of the

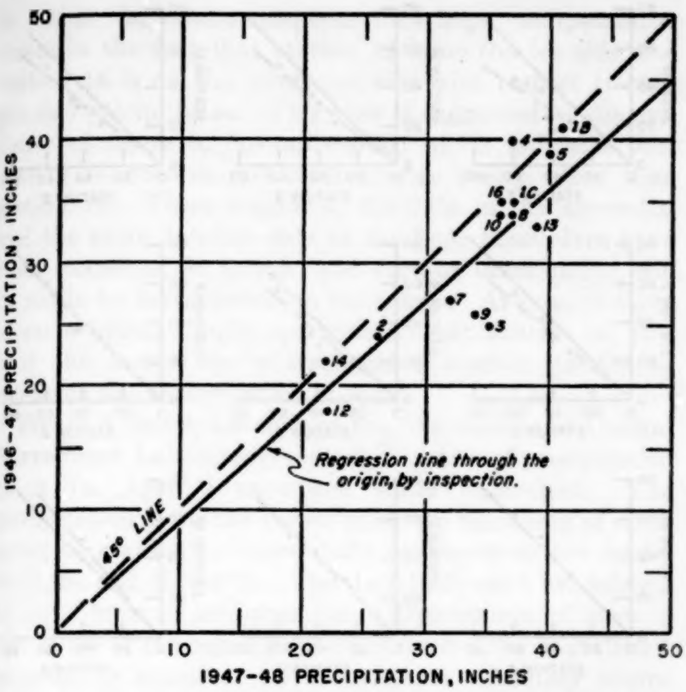


FIGURE 5.—Correlation of precipitation catch of each of several gages (numbers indicate gage) for the 1946-47 and 1947-48 seasons, October through March, Central Sierra Snow Laboratory.

seasonal total, but it is believed that this source accounts for less than one inch in the worst case. The amount of scatter indicates how well or how poorly any one of the gages would serve to locate the regression line, which is another way of saying how well a gage might serve as a consistent index, regardless of true-catch considerations.

An important fact disclosed by this figure is the great range in catch among these gages at Central Sierra Snow Laboratory. They were all on towers and all shielded. They were all within a 4-square-mile drainage area, and had an extreme range of elevation of less than 1,000 feet. Attempts to relate the respective catch of these different gages to topographic parameters of any kind, and in many combinations, were virtually fruitless. Referring again to the five sets of parameters discussed in the introduction, the only explanation is that the variation from gage to gage in Central Sierra Snow Laboratory is ascribable largely to variations in local gage site.

To show how the scatter of figure 5 varies from year to year, instead of merely for the pair of years shown, various pairs of gages have been compared for the 5-year period of record. These comparisons are shown in figure 6. In these graphs the numbers identify Central Sierra Snow Laboratory stations, for the seasons October through March. The solid lines are 45° through the origin and the broken lines are drawn through the origin, fitted to the points by inspection. It is convenient to remember that for most gages the total seasonal precipitation catch increased progressively from year to year, 1946-47 through 1950-51.

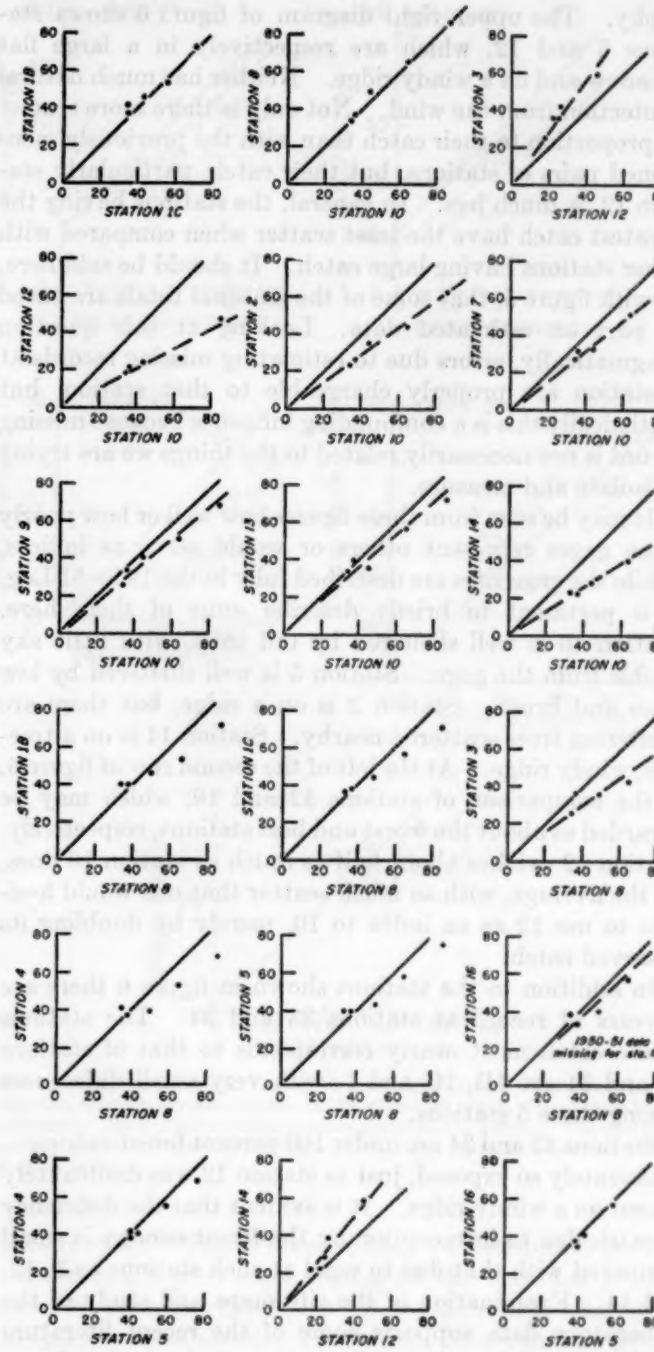


FIGURE 6.—Correlation of seasonal precipitation catch of selected pairs of stations, Central Sierra Snow Laboratory. Each point represents a season, October through March, 1946-47 through 1950-51. The solid lines are 45°, the dashed lines are regressions through the origin, drawn by inspection. Scale units are inches.

Gages 1B and 1C, which have been compared before, appear in the upper left of figure 6. The amount of scatter is small but appreciable. Stations 8 and 10, shown next on the right, show even less scatter than 1B and 1C and it is noteworthy that stations 8 and 10 are 3,000 feet apart with about 200 feet difference in elevation. Even with only 5 years data it is very unlikely that a correlation this high would occur by chance. These two stations are well sheltered by trees and/or concave topog-

raphy. The upper right diagram of figure 6 shows stations 3 and 12, which are respectively in a large flat meadow and on a windy ridge. Neither has much natural protection from the wind. Not only is there more scatter in proportion to their catch than with the previously mentioned pairs of stations, but their catch, particularly station 12, is much less. In general, the stations having the greatest catch have the least scatter when compared with other stations having large catch. It should be said here, as with figure 5, that some of the seasonal totals are based in part on estimated data. Looking at this question pragmatically, errors due to estimating missing records at a station are properly chargeable to that station, but statistically this is a confounding influence because missing record is not necessarily related to the things we are trying to isolate and measure.

It may be seen from these figures how well or how poorly some gages represent others or would serve as indices. While the gage sites are described fully in the 1950–51 Log, it is pertinent to briefly describe some of them here. Station 16 is well sheltered by tall trees, with little sky visible from the gage. Station 5 is well sheltered by low trees and brush. Station 2 is on a ridge, but there are sheltering trees scattered nearby. Station 14 is on a treeless, windy ridge. At the left of the second row of figure 6, is the comparison of stations 12 and 10, which may be regarded as about the worst and best stations, respectively. Station 12 catches about half as much as station 10 does, on the average, with so much scatter that one would hesitate to use 12 as an index to 10, merely by doubling its observed catch.

In addition to the stations shown in figure 6 there are 2 years of record at stations 33 and 34. The stations whose catch most nearly corresponds to that of stations 33 and 34 are 1B, 1C and 7, with very small differences among these 5 stations.

Stations 33 and 34 are under 100 percent forest canopy—deliberately so exposed, just as station 12 was deliberately placed on a windy ridge. It is evident that the deficiency in catch due to interception by the forest canopy is small compared with that due to wind at such stations as 3, 12, and 14. Examination of the site maps and study of the Laboratory data supports some of the recent literature to the effect that the optimum proportions of a forest precipitation-gage site, so as to minimize the combined effects of wind and interception, are a diameter of clearing approximately equal to the average height of the surrounding trees.

Some of the discrepancy in gage catch may be due to the proportions of snow and of rain in the season's catch, with the wind affecting snow catch more than rain catch. About half the precipitation for the 1950–51 season was rain, and about a third of the precipitation for the 1947–48 season was rain. Precipitation for the other three seasons was nearly all snow. The differences among storage, Friez, and Stevens gages are regarded as insignificant in affecting total seasonal catch.

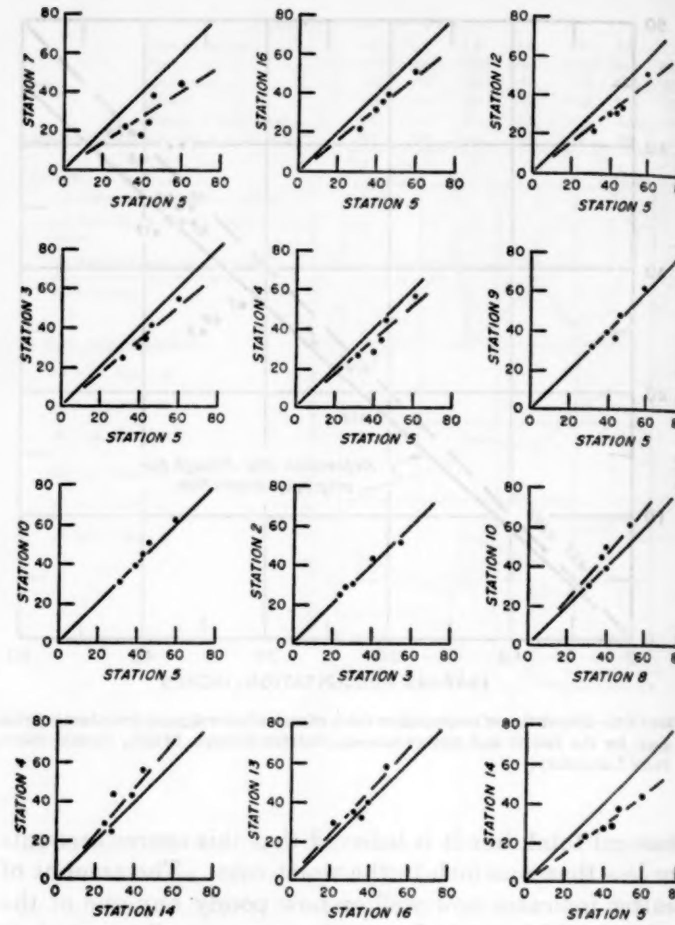


FIGURE 7.—Correlation of April 1 snowpack water equivalent at selected pairs of stations, Central Sierra Snow Laboratory, 1947 through 1951. Each point represents a season's accumulation. The solid lines are 45°, the dashed lines are regressions through the origin, drawn by inspection. Scale units are inches.

Figure 7 corresponds to figure 6, referring, instead of to seasonal precipitation, to water equivalent of the snowpack on or about April 1 each season, Central Sierra Snow Laboratory. In general, the scatter is about the same as for seasonal precipitation. Any difference between the water equivalent and precipitation scatters is probably ascribable to the peculiarities of the individual stations being compared, rather than to inherent differences in the two modes of observing winter precipitation.

Station 7 (upper left) has deficient pack compared with station 5, presumably due to the southerly exposure and early seasonal melting of the snow at station 7. Station 16 (upper center of fig. 7) has less snowpack accumulation than nearby station 5. This difference might be ascribed to interception by the high dense trees at station 16. Station 12 (upper right) and station 14 (lower right) also have less snow accumulation than station 5. Stations 12 and 14 are windy and have scanty ground cover for holding windblown snow early in the season. Speculation among many plausible influences and only a few gages is easy until one faces such facts as station 12 being exposed to the north and station 14 to the south, and being similar

in other important respects. Perhaps compensation exists in the fact that station 12 is on the lee side and station 14 is on the windward side with respect to orographic precipitation. This view is supported by the evidence of figure 6, bottom center, which indicates that station 14 does in fact receive more precipitation than station 12. These diagrams, the data in the appendix, and the more detailed data in the Logs themselves have been examined at length, and further examination will be made by investigators in the future. At present there is no evident, simple, quantitative explanation of just how the many site characteristics operate jointly to influence the accumulation of snow.

Figure 8 shows, for each of the five seasons at Central Sierra Snow Laboratory, scatter diagrams of precipitation catch vs. April 1 snowpack water equivalent. The precipitation is for the period from the beginning of snow cover at station 1, where daily observations are made, until the end of March. The data in figure 8 are subject to some error of interpretation. One source of error is the failure of the beginning date of snow cover at station 1 to properly represent all the stations. Another source is in the need for interpolating among stations where the snow surveys were not made at corresponding dates. Nearly all of the rainfall, which would complicate comparison of gage catch because of limited retention of rain in the snowpack, occurred before the dates of beginning of the seasonal pack.

In figure 8, the degree of scatter is one of the first things to notice. The next thing to notice is the change in position of each station in the pattern from year to year. Some stations retain their relative position better than others. The next thing to notice is the bias, which shows an average excess of snowpack water equivalent of about 15 percent over precipitation catch. This ratio and the absolute difference change from year to year, but no assignable causes were discovered for these changes. The degree of scatter shows that the effects of variation in local exposure are different for snowpack than for gage measurements. As the site maps and photos shown in the Logs indicate, the snow sampling points are usually clustered around the precipitation gage tower. There is, of course, considerable scatter not assignable to inherent differences in these two modes of measurement. A few individual station positions in the scatter may be noted. Station 7, as indicated earlier, and station 19 are exposed to the south and are subject to early seasonal melting. Stations 2, 12, and 14 are deficient both in precipitation catch and in water equivalent, particularly in precipitation catch—possibly because a gage or a tower measurement suffers more from a windy exposure than does a snowpack observation, where the wind is weaker being nearer the ground. Stations 5 and 9 show considerably more water equivalent than precipitation.

Stations 33 and 34, 1949–50, with 100 percent forest canopy over both the gage and the nearby snow sampling points, show slightly more gage catch than snowpack

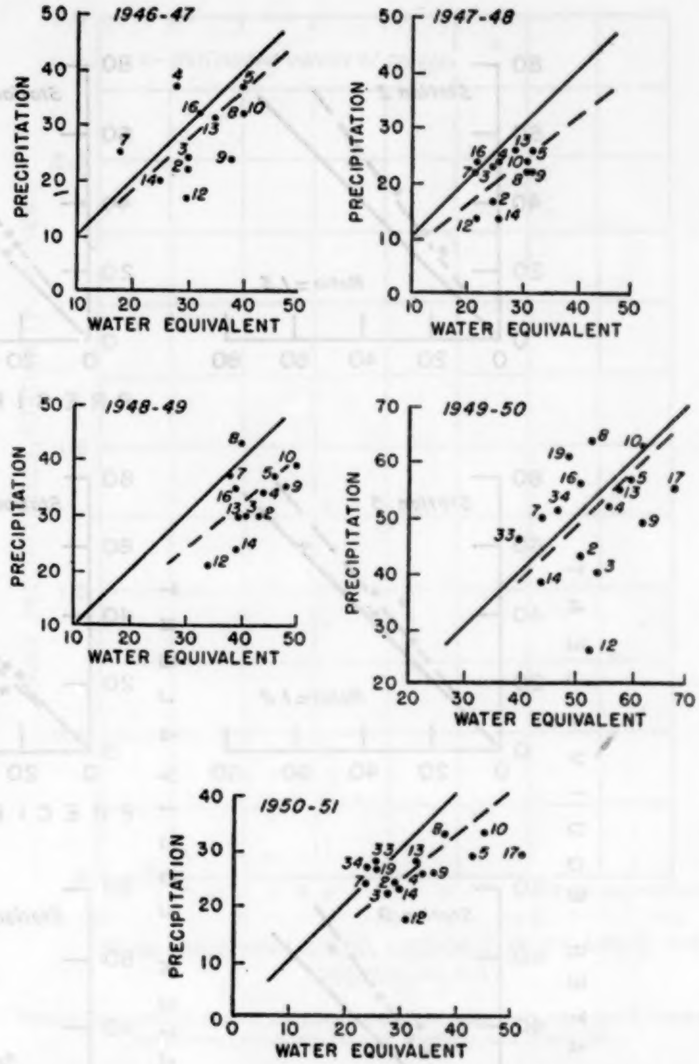


FIGURE 8.—Correlation of April 1 snowpack water equivalent and corresponding precipitation catch for each of the five seasons 1946–47 through 1950–51, Central Sierra Snow Laboratory. Each point represents a station, designated by number. The solid lines are 45°, dashed lines are regressions through the origin, drawn by inspection. Scale units are inches.

accumulation. This difference may be attributed partly to more intercepted snow falling off the branches of the trees into the gages than onto the specific points where the snowpack was sampled. This would be a random error, with no inherent bias. Possibly there is more evaporation from the natural snow surface than from the oil-covered contents of the gage.

Attempts to measure evaporation or condensation, even on a seasonal basis, by comparing snowpack accumulation with nearby gage catch involve several complications. One is the elimination of, or accounting for, snow-melt. Another complication, evident in figure 8, is the combined effect of differences in exposure, errors in measurement, and irregularities in the snowpack. The magnitude of these influences, indicated by the scatter in figure 8, is several inches and obviously obscures the net seasonal vapor exchange at the snow surface—which can hardly exceed five inches in the area studied.

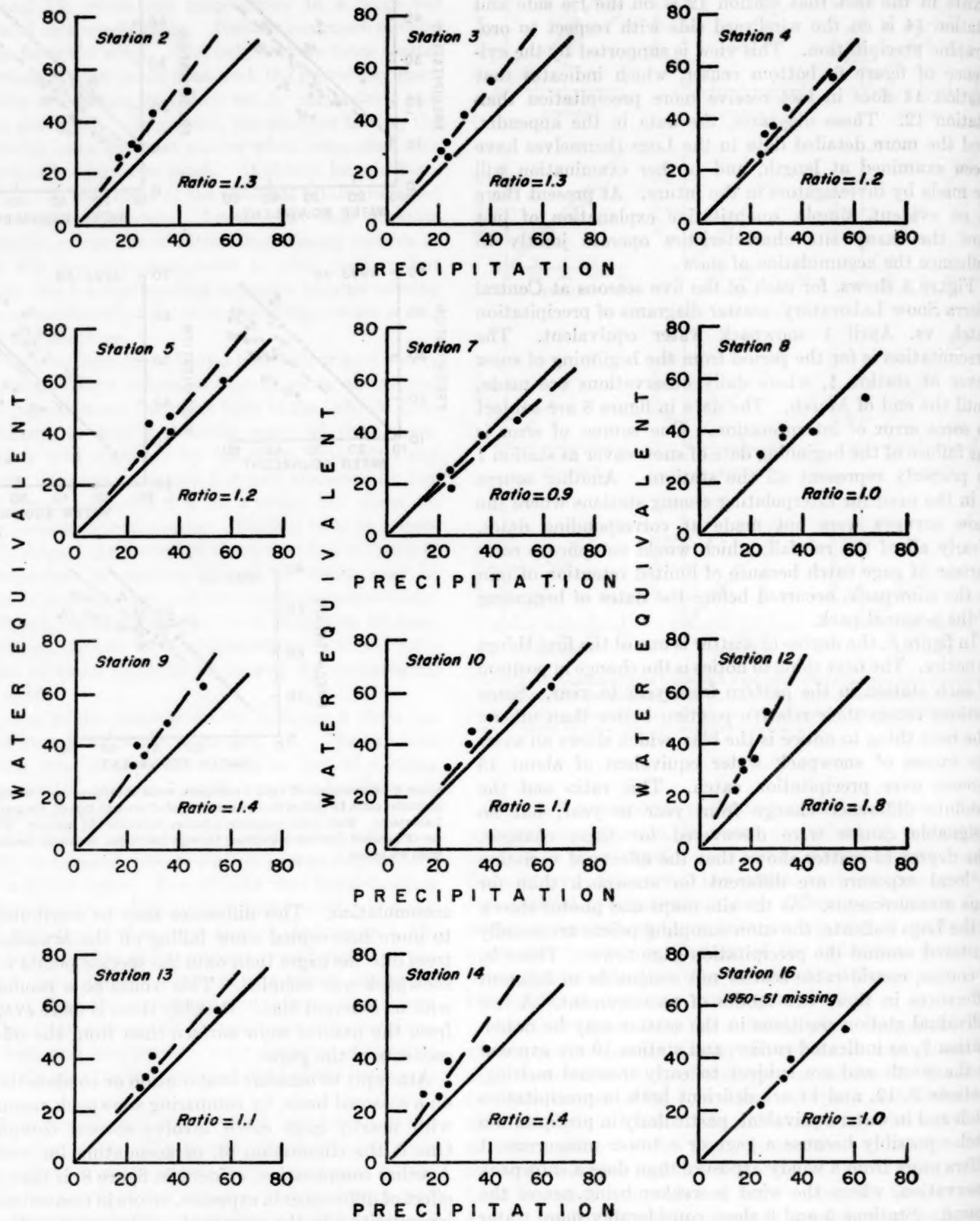


FIGURE 9.—Correlation of April 1 snowpack water equivalent with corresponding catch of snowfall for each of five seasons 1946–47 through 1950–51, by stations, Central Sierra Snow Laboratory. Each point represents a season. The solid lines are 45°, dashed lines are regressions through the origin, drawn by inspection. The ratio shown numerically in each diagram is water equivalent to precipitation. Scale units are inches.

The diminished snowpack under trees has often been ascribed to the evaporation of intercepted snow. It is hard to see why snow held in the tree canopy should evaporate much more than snow accumulated on the ground in open meadows. Possibly the greater snowpack in the open is partly a result of much of the intercepted snow eventually blowing out of the trees into the open by the wind. This snow would be measured by snow courses in the open, but not by gages mounted on towers, and might account for some of the excess of average snowpack water equivalent over gage catch.

Figure 9 shows the relation of precipitation catch to water equivalent at each station, with each year of record being shown by a point in the scatter. These diagrams show the general excess of snowpack over gage catch referred to earlier in connection with figure 8. Attempts to generalize on the basis of particular station features have had limited success. The greatest difference is at station 12, which has been described earlier. The best correspondence is at station 16 where a canopy of huge trees nearly covers both the course and the gage. Water equivalent was not observed at station 1.

It may be noted, in general, from examination of figures 6, 7, 8, and 9, that there is about the same amount of scatter in the year-to-year precipitation catch, year-to-year snowpack accumulation, and snowpack vs precipitation catch at most of the stations, thus indicating no marked superiority in any of the methods of estimating seasonal accumulation of snowfall.

EFFECTS OF WIND

Parts of the foregoing discussion refer to the importance of wind in affecting gage catch, and the question naturally arises: how much of the precipitation naturally occurs during periods of strong wind? Figure 10 shows the relation of daily precipitation at station 1B to mean daily wind 50 feet above the ground at station 3 for January, February, and March 1951. The wind at station 3, while it is 6,000 feet from station 1, is measured in an open meadow and is regarded as a better and more independent indication of daily windiness than the sheltered exposure at station 1. A low but positive correlation (estimated to be about 0.6) is evident. In correlating precipitation with wind it is seen that in spite of a tendency for windiness to decrease the catch, the natural occurrence of precipitation is associated with storms that are accompanied by considerable wind. Thus, wind is important in that it is usually present during significant precipitation.

In spite of examination of many scatter diagrams and trial of many kinds of measures of site characteristics, there was negligible success in an effort to relate precipitation catch to objectively determined site parameters. Elemental parameters that were tried include ratio of diameter of forest clearing to average height of the trees surrounding the clearing in which the gage was located, height of tower above the ground, shape and orientation

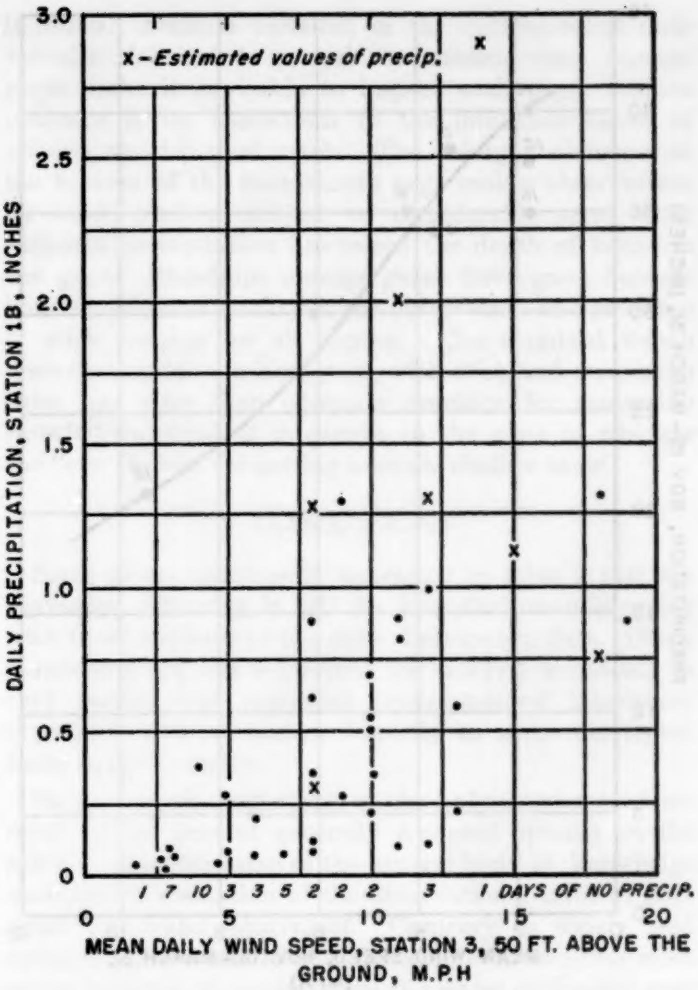


FIGURE 10.—Relation of daily precipitation catch to mean daily wind speed, Central Sierra Snow Laboratory, January, February, and March 1951.

of the clearing, and in the case of more open terrain the distance, size, and direction of obstructions. Enough site elements could be devised to provide a unique solution because of lack of replication, but the essential problem was not solved.

Figure 11 shows a plot of precipitation catch vs wind, by stations. The negative effect of windiness on catch has been noted many times in the literature. A definite negative correlation is evident among the stations each year at Central Sierra Snow Laboratory, the example shown being 1948–49. Except for stations 1B and 1C, where the anemometers are only 8 ft. above the ground or snow, and better sheltered than the precipitation gages, the anemometers are attached to the precipitation gage towers only a few feet from the gage orifices.

It is evident that mean hourly wind speeds of less than 2 to 4 m. p. h. are associated with the stations that have been shown earlier to have the greatest and most consistent precipitation catch. No Central Sierra Snow Laboratory stations other than these shown here have wind speed data for relating precipitation catch to wind speed.

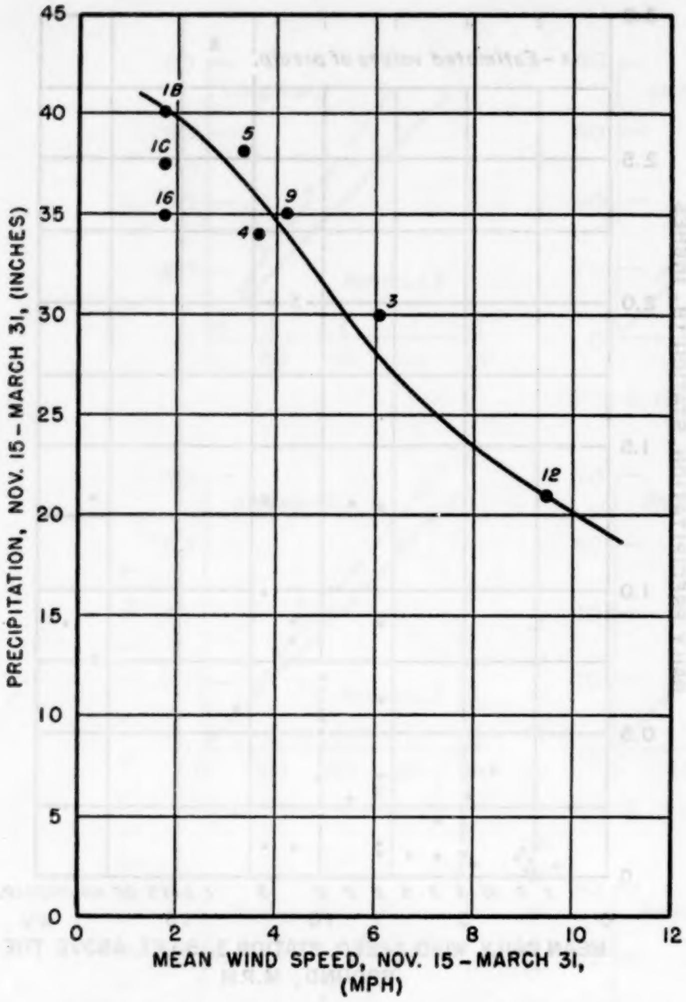


FIGURE 11.—Relation of seasonal precipitation to average seasonal wind speed, by stations (designated by number), Central Sierra Snow Laboratory 1948–49. During publication it was discovered that the point for station 3 should have been plotted at 32 instead of 30 inches of precipitation. The line, however, remains as a good representation of the relation for the several years studied.

Experience at the Laboratories indicates that well-sheltered sites are to be desired, and that windiness is a measure of degree of shelter.

The line in figure 11 was drawn to fit the points, and to meet the requirements of a definite intercept on the Y-axis and an asymptote near the X-axis. While there are too few points in this figure to define conclusively the effect of wind on catch, it is estimated that the correlation accounts for more than half the variance in gage catch among the varying station sites.

CAPPING

Capping is the adherence of snow to a precipitation gage, with the implication of deficient catch because of the cap. There are records of huge caps that envelop and completely obstruct the gage orifice. More frequently, capping only partly obstructs the gage orifice, having the effect of reducing the orifice area. A cap built upwind on the outside of the gage may not obstruct the opening, but may affect the catch through a change in the aerodynamic shape of the gage. Capping of unattended gages is sometimes evidenced by sharp rises in the pen trace at the time the cap melts and slides down into the receiving bucket.

Capping is difficult to evaluate, and the magnitude and importance of its effects vary greatly according to circumstances. Attempts to generalize on the basis of limited observations have led to controversy. At station 1B at the Central Sierra Snow Laboratory there were an average of six instances of capping each year—some observed and more inferred from examination of the gage charts. In spite of this incidence of capping it may be noted that the seasonal catch seems to have been good.

Other Laboratory stations seem to have had about the same experience as station 1B with regard to capping, but with a few notable exceptions. One type of exception was associated with experiments in using timber for gage towers. Large-size structural members have an excessive horizontal projection of surface on which snow can accumulate and build up to effective caps. The other type of exception might not be regarded as true capping, but resulted from using towers that were too low, and there were instances, while getting acquainted with the weather at the Laboratories, of deep snow completely covering the tower and gage.

In general, the laboratory experience showed that extreme windiness had more effect on gage catch than did capping or any other process. It is possible that unattended storage gages have at times had deficient catch incorrectly attributed to caps that were observed when the gages were serviced, rather than to the less obvious but persistent wind—particularly at poorly sheltered sites.

At a well-sheltered site a cap may build up but will eventually contribute to the gage catch as the sharp orifice rim cuts its way through the settling snow of the cap—essentially taking a snow core upside down. At such sites, there is too little wind to blow the cap off the gage and lose it from the catch. The error from capping is then one of timing rather than of total catch.

Efforts to treat gages with hydrophobic or anti-icing materials have had little success. There have been many experiments with heating the orifices of gages, with some reports of success, and other reports that the heating causes evaporation of the incipient cap, with as much loss as from the effects of the cap itself. There is fairly general agreement that frequent servicing is very helpful. Instead of waiting for the cap to cut its way into the gage, servicing of the gage includes gentle pushing of the snow cap into the receiving bucket. At the Snow Laboratories servicing was at monthly or more frequent intervals.

Present practice with storage gages is to use flexible shields so that movement of the leaves by the wind shakes off snow that might otherwise build up into a cap. For

snow that accumulates at the orifice of the gage instead of the shield, some melting of the cap is induced by absorption of solar radiation by black paint used on the gages. At sites having adequate natural shelter—small clearings in a forest—shields are unnecessary. Such sites are relatively shady until late in the spring so that black paint would have little effect.

GAGE SITE

The conclusion that a small clearing is best for gage exposure appears to be at variance with the traditional rule that a gage should be no nearer an obstruction than two or four times the height of the obstruction. This old rule evidently applies to single large obstructions, such as buildings, and not to a symmetrical opening in a forest or orchard.

It is evident that shielding does little to improve an inherently poor gage site. It is also evident that variations in natural winter precipitation over distances of a few miles and with elevation differences of a few hundred feet are very small compared with the variation in catch ascribable to differences in local site. Therefore, subject to convenient accessibility for observation and servicing, a gage can sample the storm experience and large-scale orographic parameters, and still be located anywhere within a rather large area provided the site is well sheltered.

The choice of gage site might be aided by means of a small portable anemometer, tying in the short-period wind data with a central station, just as with altimeter surveying. A time may come when shields will rarely be necessary or justified, and, whenever a windy site must be used, a correction factor in terms of the windiness of the site can be applied to the precipitation catch, just as corrections are now made for height of anemometer.

INSTRUMENTAL PRECISION

In discussing the effects of weather and physical exposure on measurement of winter precipitation it is pertinent to refer briefly to the inherent precision of the measuring instruments.

The spring scales used for weighing snow cores can seldom be read with a precision of much better than a half inch of water equivalent. This is particularly true of the light cylindrical type of scale in common use because of its convenient portability. This degree of precision is consistent with the sampling error of water equivalent. The dimensions of snow cutters and tubes commonly used are adequately precise.

The weighing mechanism of most recording precipitation gages is precise to about one hundredth of an inch. This degree of precision is required for measuring light rains and is more than adequate for measuring precipitation in the form of snow. The receiving ring of standard and recorder gages is usually dimensionally exact when new, but occasional attention may be necessary to keep it round. Possible variation in the dimensions of individually fabricated conical Sacramento-type storage gages make it advisable to inspect each gage, and to calibrate it for corrections to the published tables of volume vs. depth of catch. The enlarged diameter at the bottom of the Sacramento gage makes observations by stick reading subject to considerable error until sufficient precipitation has raised the depth of liquid in the gage. Standpipe storage gages have good balance between inherent quality of the observation and precision of stick reading for all depths. The standard 8-inch diameter by 24-inch high gage, with stick and measuring tube, has more than adequate precision for measuring snowfall—whether it is caught in the gage or whether the "can" is used for cutting a core of shallow snow.

CONCLUSIONS

Some of the statements appearing in table 2 and the discussion following it will be identified as originating with these analyses of the Snow Laboratory data. Other statements are not supported by analysis appearing in that report, but represent undocumented laboratory experience and are included mostly to make the report fairly comprehensive.

In general, the experience at the Laboratories confirms much of the present generally accepted opinion on the subject. Amplification of the general body of knowledge includes an evaluation of the observational error in gage catch and water equivalent. Contrary to widely held opinion, there seems to be convincing evidence that most of the variation in precipitation and water equivalent may be attributed to variations in the local exposure of each observing station, and that the annual pattern of "true catch" over rugged areas as large as 10 sq. mi. is relatively flat. The only weather elements that seriously affect measurement of winter precipitation are wind, and, secondarily, elements combining to cause freezing, or—with snow surveys—also heating. The average observed water equivalent is apparently very nearly a measure of its true value. The average observed precipitation for all the laboratory gages was about 15 percent deficient, due almost entirely to the effects of wind on the relatively high gage towers that are necessary in places where deep snowpacks accumulate. The laboratory gages exposed with the best shelter, stations 8 and 10 of Central Sierra Snow Laboratory, for example, appeared to have very nearly 100 percent true catch. Variation due to type of gage is fairly small, with the important conclusion that the effects due to differences in gage, including shielding, are much smaller than the effects of physical features of local station site.

Only a little has been said about frequency of servicing as an influence on quality of data, and it would be hard to assign it a measure but it should be emphasized that the laboratory experience showed definitely that frequency

and skill of servicing is extremely important—not only for reducing relatively small so-called random error, but to reduce loss of record. Nearly all the extraneous influences on gage catch tend to reduce it, and the generally held opinion that the most catch is the best catch seems to be supported, except in the case of obvious blunders in exposing a gage. The laboratory data show rather definitely that the gages with the poorest catch also are the most erroneous with respect to having index value.

TABLE 2.—*Effects of principal weather and exposure elements on precipitation and snowpack measurements*

Element	Effect on gage catch	Effect on snowpack water equivalent
Weather:		
Wind:		
Drifting snow	Nil, gage on tower	Increases small-scale variability.[1]
Turbulence	Deficient catch [1]	Increases small-scale variability.[1]
Melting:		
Solar	[Melting is beneficial and the melt water is retained in impervious gage.]	Early spring melting loss on south slopes.[1, 2]
Warm soil		Little late-fall melting loss.[1, 2]
Warm air		Early spring melting loss at low elevations.[1, 2]
Vapor exchange:		
Condensation	Very slight in gage	Small gain to pack,[1, 2]
Evaporation	Nil, with oil film	Small loss from pack.[1, 2]
Rainfall	Normal part of catch	Part may pass through pack.[1, 2]
Freezing:		
During deposit	Capping and loss of catch [1]	Makes measurement difficult.
After deposit	Makes measurement difficult.[1]	"Corky" snow with loss of core.[1]
Exposure of site:		
Obstructions:		
Interception	Slightly deficient catch [1]	Same as for gage.
Sheltering	Helps reduce bad wind effects.[1]	Reduces small-scale variability.
Retention	Does not apply to gage	Excess pack due to snow-fence effect.[1]
Soil surface:		
Roughness	Does not apply to gage	Increases small-scale variability.[1]
Slope	Small effect on gage	Small effect on pack.[1]
Permeability	Does not apply to gage	Loss of melt water or rain.[2]

[1] Item is important and is discussed in text.
[2] Item raises question of purpose of measurement: Would be detrimental to the measurement as an index of seasonal precipitation but inherent and necessary in a measurement of snowpack as such where the interest is essentially in the residual pack regardless of its history.

Discussion of important effects of weather and exposure on gage catch:

Wind turbulence.—May cause loss of more than 50 percent, even on a seasonal basis; shielding may help as much as 20 percent, but best solution is better choice of natural site so as to take advantage of sheltering effect of surrounding trees, etc., and reduce the mean wind speed to less than about 2 m. p. h. at the gage orifice.

Capping.—Serious in some instances; frequent servicing helpful, also nature of gage: black paint, good shape, etc.; experiments with hydrophobic coating, heating, and vibration have been unsuccessful to date. Frequency of occurrence is difficult to estimate. Many small caps melt their way into the gage and do not affect the total catch of a well-sheltered gage, but adversely affect the timing with recording gages.

Freezing after deposit.—Makes stick measurement difficult but is not serious if the gage has ample capacity. Antifreeze helpful; occasional servicing reduces stratification.

Interception.—Reduces seasonal catch at most about 15 percent in the environment studied.

Sheltering.—While large single obstructions are harmful, and express wind direction as well as precipitation in nearby gage catch, a gage, exposed in a symmetrical forest or orchard clearing having a diameter about equal to the height of the trees, will gain more from the reduction of wind effect than it will lose from interception.

Drifting snow.—The effects of drifting and drifted snow, and of wind turbulence, may all be grouped under one heading. The net effect is less near the ground than at the usual height of a gage on a tower. The effect is minimized by using a large number of points per course; no bias seems evident.

Solar melting.—On south slopes, melting may occur so early in the season that such a course would not be representative for estimating water supply.

Warm soil.—The loss from a snowpack due to warm soil is usually very small, and would not be a serious deficiency with respect to water-supply forecasting except in instances of intermittent snow cover for much of a normally long snow-cover season.

Warm air.—At low elevations early season melting may reduce the snowpack water equivalent to a degree making it nonrepresentative for water-supply considerations. As a measure of existing snowpack, for considering its effect on runoff from rain in flood forecasting, low-elevation snow data is very helpful.

Condensation and evaporation.—These elements often balance and probably seldom exceed five inches water equivalent loss or gain for a season.

Rainfall.—The capacity of a snowpack for storing rain or even melt-water is usually less than 5 percent of the water equivalent of the snowpack.

Corky snow.—As with capping of a gage, the cause is the sticking of snow to the measuring instrument because of freezing of water in the snow. Skill in making the measurement is helpful, but there are times when wet snow in the pack is chilled and plugs the tube so that a satisfactory core is impossible. It is difficult to estimate the frequency of occurrence of serious trouble from corky snow. Some regions rarely have it.

Retention by obstruction.—At some sites low brush and weeds may produce a snow-fence effect wherein excessive and nonrepresentative pack may accumulate early in the season until the brush is enveloped. This effect is seldom serious, but can be controlled as can the effects of rough ground and rocks by proper preparation or selection of the site.

Soil surface roughness.—Similar to the above discussion

of obstruction. Even a smooth-looking ground surface may have a standard deviation of elevation of two or three inches within a few feet of a snow stake. The deposited snow tends to have a more streamlined shape than the ground surface so that the thickness of the snowpack may have considerable variation over very small distances. While several points are necessary for good sampling of a snow course, the points do not need to be as far apart as has been the practice.

Soil slope.—Ponded water makes it important to avoid marshy areas and drainageways. Steep slopes are to be avoided, also places where there is a sharp change in slope, because of irregularity in the downhill movement of the snowpack and because of damage to, or loss of, the snow stakes affected by the mass movement of the snow.

ACKNOWLEDGMENTS

R. D. Tarble helped with many of the analyses. Helpful criticisms and suggestions were made by R. W. Schloemer, A. L. Shands, and others of the Weather Bureau staff, and by members of the Corps of Engineers Snow Investigations.

APPENDIX

The tables and maps on the next four pages presenting general characteristics and locations of the stations at the Central Sierra and Upper Columbia Snow Laboratories were taken from the *Hydrometeorological Logs* of the Cooperative Snow Investigations. The background, organization, and objectives of the investigation, with brief descriptions of each of the field laboratories and tables showing the instrumentation and observational program, have been given in *Technical Report* 6–4 of the Cooperative Snow Investigations.

A *Hydrometeorological Log* has been published for each water year (begins October 1) of record for each of the laboratories. Each log has a brief text, a topographic map of the laboratory area, a bar chart showing the availability and status of observational data, a summary of the stations and types of data for each water year, a graphic synopsis of daily values of selected representative elements, and an average of 200 pages of numerical data. Some of the logs present special summaries and tentative results of the revisions. The logs of 1950–51 for the Central Sierra Laboratory and of 1948–49 for the Upper Columbia Laboratory contain detailed station site maps and pertinent photographs. In all, about 2 million observations are tabulated in the logs. A few additional tabulations and all the original field notes and recorder charts are on file. Considerable selected data are on punch cards. Questions about quality, circumstances, and selection of data; about availability of unpublished data; or about reports other than the logs, may be referred to the Division Engineer, South Pacific Division, Corps of Engineers, U. S. Army, San Francisco, Calif., or to the Chief, Hydrologic Services Division, U. S. Weather Bureau, Washington, D. C.

While this report is a description of some of the effects of winter weather and exposure on the performance of precipitation gages, it may be of interest to note the other elements that have been measured and are recorded in the logs: incident and reflected solar radiation; air temperature and humidity at many stations and at various heights above the ground or snow surface; snowfall, snow depth, water equivalent, density, and other snow properties at many stations; stream flow and ground water stage; snow, soil, and water temperatures; wind speed and direction; soil moisture; barometric pressure; and weather (cloudiness, etc.).

SUMMARY OF STATION SITE CHARACTERISTICS
CENTRAL SIERRA SNOW LABORATORY

1	2	3	4	5				6		7	
Station Number	Elevation Feet	Slope %	Aspect °Az	Exposure Sector: Azimuth Limits	Dominant Direction	Size °Arc	Lowest Point	Shelter Sector: Size °Arc	Highest Point	Canopy Cover %	VEGETATION AND REMARKS
1 (Hq.) g.b.	6895	10	270	170-270	SW	100	120	260	585	15	(7) Open area approximately 150' diameter.
1 (Hq.) sh.	6885	15	250							25	(7) Open area approximately 50' diameter.
1 (Hq.) py.	6885	10	210							10	(5) On North side of open area approximately 100' diameter. In area of exposed bedrock.
2	7325	10	310	220-20	NW	160	525	200	145	10	(3) Partially within small open grove. Some points shaded by trees. Near top of ridge.
3	7170	<5	200	220-250	SW	30	100	330	430	<5	(1) In North part of grassy meadow. Refers only to Met. Sta. and snow course.
4	7245	5	330	50-100 230-280	SW	100	75	260	305	10	(3) Among scattered trees and small open groves. Some points shaded. Irregular surface of bedrock and boulders.
5	g. 7370 sc. 7375	5	170	130-180	SE	30	120	330	530	5	(4) Willow thickets near all points, covered by snow in winter. Small trees near points 1 and 2.
6	7835 7905	25	200	90-290	S	200	460	160	310	10	(3) Part of course among bedrock outcrops and small boulders.
7	g. 7170 sc. 7155 - 7225	20	160	70-240	S	170	310	190	405	25	(8) Many boulders and outcrops of bedrock near points.
8 points A-E and gage	7740	5	130								
8 points F - I	7760 -7810	30	190	100-170	SE	70	440	290	475	<5	(3) F, G, H on rocky slope.
8 points J - L	7740 -7765	20	40								Bedrock outcrops near K and L.
9	g. 7510 sc. 7505	<5	190	160-230	S	70	335	290	490	<5	(1) Point 6 near willow thickets.
10	g. 7570 sc. 7565	15	200	140-210	S	70	215	290	810	5	g. (7) sc. (5) Snow course at base of 30% slope.
11	7250	25	200	100-130 180-260	SW	110	215	250	375	5	(7) In open area approximately 150' in diameter, open toward SE.
12	g. 7550 sc. 7555	15	330	250-80	N	190	400	170	155	<5	(3) Far from forest. Scattered trees and small open groves. On spur 150' lower than main ridge.
13	g. 7035 sc. 7040	g. <5 sc. 5	g. 260 sc. 130	180-250	SW	70	165	290	440	<5	g. (6) Cage in willow thicket near Castle Creek. sc. (7) Part of snow course among granite boulders.
14	7480	20	220	90-280	S	190	255	170	495	<5	(3) Among low shrubs and outcrops of bedrock.
15	8260	35	200	120-300	SW	180	770	180	840	0	(1) On crest of barren rocky spur.
16	g. 7510 sc. 7505	30	70	80-140	E	60	210	300	705	40	(9) In old growth fir.
17	g. 7745 sc. 7740	15	110	80-170	SE	90	345	270	470	<5	(1) On small bench of approximately 10% slope. Slope below site 15-20%.
18	7850	20	190	130-220	S	90	375	270	1250	15	(7) Points A, B, H, G shaded by trees.
19	7340	10	160	70-230	S	160	365	200	480	35	(7) In small open area. All points shaded by trees. Snow course among outcrops of bedrock.
20	7325	20	350	280-40	N	120	250	240	375	10	(7) Points C and D shaded by trees.
21	7780	15	220	170-280	SW	110	335	250	1020	15	(7)
22	7395	15	60	90-130	E	40	220	320	405	5	(7) Points E and F shaded; F under forest canopy.
25	7300	5	130	0	SE	0	0	360	340	10	(9) Shelter cabin.
26	7310	<5	130	110-150	SE	40	100	320	360	10	(1) Station in lower end of meadow, frequently marshy.
27	8245	50	200	130-280	S	150	720	210	860	0	(1) Rocky slope. No trees within 1,000'.
28	6910	10	150	150-270	SW	120	140	240	490	20	(8) Among boulders and bedrock outcrops.
29	7525	5	170	120-210	S	90	300	270	575	5	(7)
30	7350	20	340	0-60 250-340	N	150	380	210	320	10	(9)
31	7190	10	320	240-270	W	30	100	330	510	10	(9)
32	8000*	50	170	130-200	S	70	480	290	1100	10	(1) Rocky Slope. Small grove of tall trees 25' northeast of gage. Nearest tree about 25' from gage.
33	7415*	20	240	140-170	SE	30	170	330	560	20	(9) Closed canopy fir forest.
34	7040*	5	230	190-250	SW	60	290	300	410	20	(9) Closed canopy lodgepole pine forest.

LEGEND AND DEFINITIONS

Column

2-4 Values are means for installation area, except in cases of marked variation.

2 Elevation in feet above m.s.l. g = ground elevation at precipitation gage. sc = mean elevation of points in snow course. To nearest 5'.

3 Slope: Dip of surface over horizontal interval of 200'. To nearest 5%.

$$\text{Slope} = \frac{\text{Vertical interval}}{\text{Horizontal interval}} \times 100$$

4 Aspect: Orientation of slope to nearest 10° Az. Az = clockwise angle from true north.

5 Exposure sector: That sector of a circle of 1/2 mile radius, centered in the installation area, within which there is no land higher than the station. Azimuth limits of sector to nearest 10°. Dominant direction of exposure to nearest of 8 compass points. Angular size of sector in degrees. Lowest point = elevation difference between station (at gage) and lowest point in exposure sector, to nearest 25'.

6 Shelter sector: That sector of a circle of 1/2 mile radius, centered in the installation area, within which there is land higher than the station. Size = 360° - size of exposure sector. Highest point = elevation difference between station (at gage) and highest point in shelter sector, to nearest 25'.

g : Precipitation gage.
sc : Snow course.
* : Estimated.
g.b. : Battery of precipitation gages.
sh. : Instrument shelter, mast and snow stake.
py : Pyrheliometer and Lysimeter site.

Revised 9-5-52

Column 7

Canopy cover: Tree canopy cover within a circle of approximately 400' diameter, approximately centered in the installation area. To nearest 5%. From aerial photos.

The following vegetation characteristics refer to an area within 100' of the points of the installation.

(1) Away[1] from forest margin; ground clear.
(2) Away[1] from forest margin; thickets.
(3) Away[1] from forest margin; scattered trees.
(4) Away[1] from forest margin; thickets and scattered trees.
(5) Near[2] forest margin; ground clear.
(6) Near[2] forest margin; thickets.
(7) Near[2] forest margin; scattered trees.
(8) Near[2] forest margin; thickets and scattered trees.
(9) Within forest.

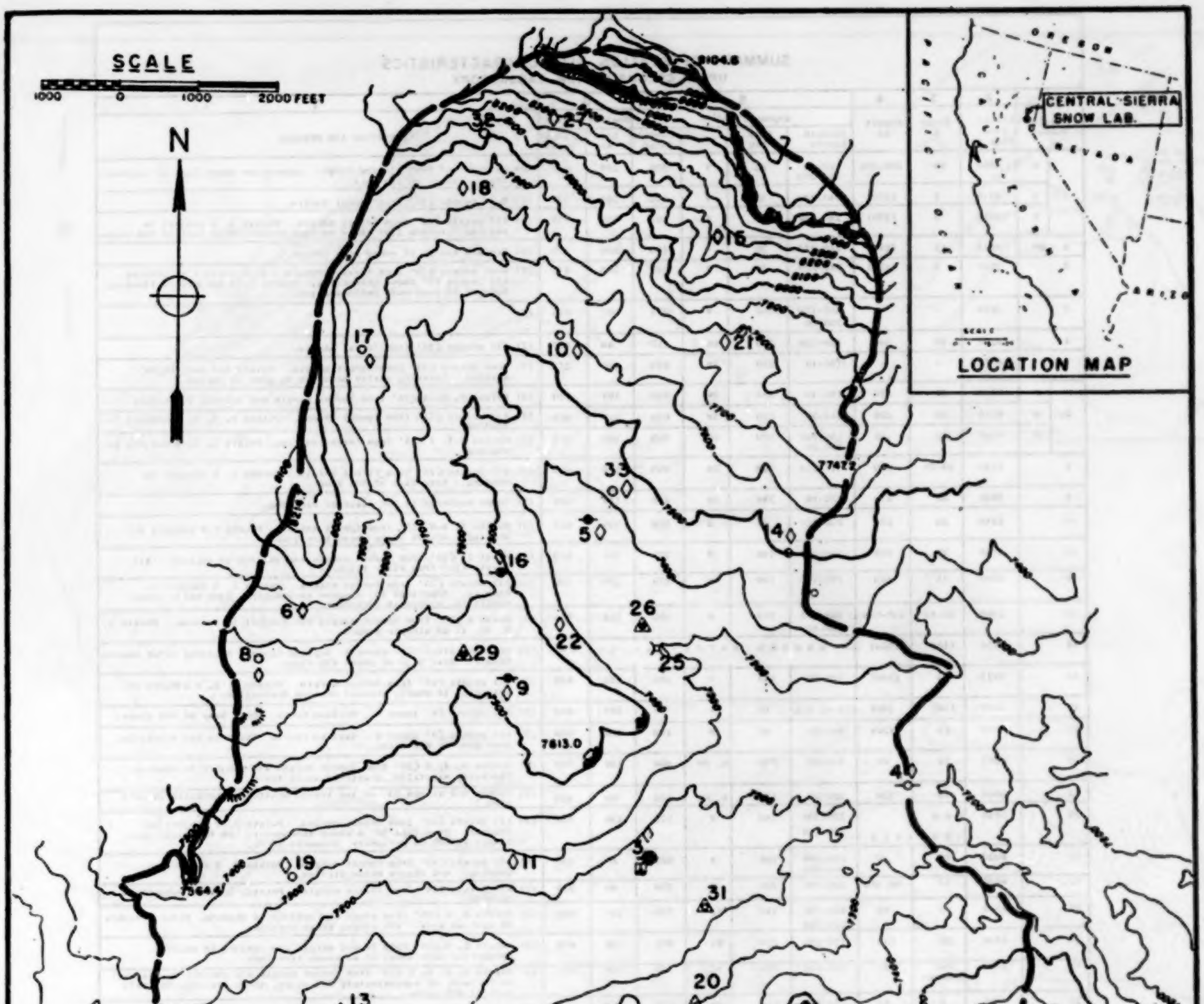
1. Margin of relatively dense forest >100' from most or all of the points.

2. Forest margin <100' from most points.

Open area: Non-forested area.

Shaded by trees: Trees cast shadow over sampling point at times during middle part of day.

NOTE: Not all stations listed above were active during the 1951-52 water year. See "Status of Laboratory Observations" for current year.


SCALE
1000 0 1000 2000 FEET
N
LOCATION MAP
OREGON
NEVADA
CENTRAL SIERRA SNOW LAB.
LEGEND
MEASUREMENTS TAKEN NON RECORDING RECORDING
PRECIPITATION
TEMPERATURE
PRECIPITATION AND TEMPERATURE
PRECIPITATION, TEMPERATURE & RADIATION
SNOW COURSE
STREAMFLOW
GROUND WATER WELLS
SNOW TEMPERATURES, SOIL TEMPERATURES, AND SOIL MOISTURE
LYSIMETER, TEMPERATURE AND WIND PROFILES
RIMROCK AND KNOBS
100 FOOT CONTOURS
BOUNDARY OF BASIN
LOCATION OF STATIONS FROM JAN. 1946 TO JAN. 1952
CENTRAL SIERRA SNOW LABORATORY
SHOWING LOCATION OF HEADQUARTERS AND FIELD STATIONS
COOPERATIVE SNOW INVESTIGATIONS
JANUARY 2, 1952

SUMMARY OF STATION SITE CHARACTERISTICS
UPPER COLUMBIA SNOW LABORATORY

1		2	3	4	5				6		7
Station Number		Elevation Feet	Slope %	Aspect °Az	Exposure Sector				Shelter Sector		VEGETATION AND REMARKS
					Azimuth Limits	Size °Arc		Lowest Point	Size °Arc	Highest Point	
1	A	4960	25	230-350	20-40 240-280	60	W	200	300	600	(5) On crest of west sloping ridge. Anemometer above tops of adjacent trees, except to the east.
1	B	4840	5	(270)	240-270	30	W	100	330	725	(2) Most points <25' from forest margin.
1	C	4845	5	(270)	240-270	30	W	100	330	725	(2) All points <25' from forest margin. Points 1, 3 subject to shading. Points <10' above Skyland Creek. Near foot of 25% slope.
A - H#		4845	<5	(230)	240-270	30	W	100	330	725	(5) Beneath canopy of young pine forest.
2		4825	5	(150)	240-270	30	W	125	330	875	(2) Most points <25' from trees. Points 1-4, 9 subject to shading. All points <5' above Bear Creek. Points 7-11 subject to flooding. Subject to road dust contamination.
3		5225	-	-	100-170 250-20	200	W	375	160	675	(6)
4		5360	10	340	200-120	280	NE	150	80	400	(2) All points <25' from forest margin.
5		6175	-	-	120-10	250	SW	675	110	375	(3) Most points <25' from forest margin. Points 1-3 subject to shading. Clearing partly occupied by pond in spring.
6	A	6340	30	210	140-40	260	SW	650	100	250	(3) Points 2, 3, 4 <25' from forest margin and subject to shading.
6	B	6315	15	220	140-30	250	SW	625	110	275	(3) All points <25' from forest margin. Points 2, 3, 5, 6 subject to shading.
6	C	6320	30	180	130-290 350-30	200	SW	625	160	275	(3) Points 1-4, 7 <25' from forest margin. Points 1, 2, 3 subject to shading.
8		7155	20-35	260	110-310	200	SW	850	160	400	(3) All points <25' from forest margin. Points 1, 6 subject to shading. Near base of 50% slope.
9		7050	20	220	130-10	240	SW	850	120	500	(2) Tower centered in 30' diameter clearing.
10		6240	35	250	250-310	60	W	350	300	800	(3) Points 1, 4-6 <25' from forest margin. Points 4-6 subject to shading. 50-60% slope above installation.
11		5780	20	230	160-300	140	W	375	220	675	(4) Point 2 <25' from forest margin and subject to shading. All points <10' from alder thickets.
12		5300	15	190	110-300	190	W	225	170	750	(4) All points <25' from forest margin. Points 2, 3 subject to shading. Tree tops 40' + above anemometer. Some small trees, windfalls, alders in clearing.
13		5300	25-55	190-240	100-180 210-10	240	W	400	120	650	(3) Point 8 <25' from forest margin and subject to shading. Points 1, 2, 10, 11 on steeper slopes.
14		5150	(10)	(310)	- - G R O U N D W A T E R - - - - - - - - - - - -						(7) On flood plain, <5' above W. Skyland Creek. Standing water nearby. Brushy. Near base of short 45% slope.
15		5250	<5	(240)	140-10	230	W	425	130	650	(3) All points <25' from forest margin. Points 2, 3, 4 subject to shading. In poorly drained shallow depression.
16		5150	(10)	(60)	310-to 310	10	-	50	350	800	(7) All points <6' above W. Skyland Creek. Near base of 40% slope.
17		5500	<5	(30)	340-20	40	N	150	320	950	(7) All points <2' above W. Skyland Creek. Thickets and windfalls. Near base of 60% slope.
18		5860	15	60	140-10	230	S, NW	400	130	550	(3) Points 3, 4, 5 <25' from forest margin and subject to shading. Thickets, windfalls, scattered small trees.
19		5000	10	120	120-30	270	S, NW	450	90	400	(1) Points 4-7 within 25' of low trees. Scattered windfalls in site area.
20		5950	S E E R E M A R K S		230-300 330-140	240	N	525	120	725	(3) All points <25' from forest margin. Points 2, 3 subject to shading. Tree tops 20' + above anemometer. On top small spur. Slopes to 50% on periphery, steepest to NE.
21		6000	20	40	230-160 200-290	280	N	600	80	350	(2) All points <25' from forest margin. Points 2, 3 subject to shading. 40% slopes below station.
22		6050	25	40-100	330-290	320	N	550	40	250	(2) All points <25' from forest margin. Points, 1, 6, 7 subject to shading.
23		5770	20	90	320-130 220-260	210	NE	725	150	450	(1) Points 3, 4 <25' from trees and subject to shading. Alder thickets in station area. 40% slopes above station.
24		5280	20	150	270-130	220	NE	475	140	675	(3) Points 2, 3 <25' from forest margin and subject to shading. Anemometer near level of adjacent tree tops.
25		5290	See Remarks	360	270-130	220	NE	475	140	675	(3) Points 3, 4, 5, 6 <25' from forest margin and subject to shading. on surface, of approximately 10% slope, above drainage-way with side of 60% slope.
26		5295	5	90	70-180 230-330	210	NW	275	150	600	(6)
26A		5300	Aprx. 5	-	- - G R O U N D W A T E R - - - - - - - - - - - -						(6)
27		5010	20	130	150-180	30	S	175	330	1100	(1) Point 3 <25' from group of trees. No points subject to shading. 60 to 70% slopes on valley sides above station. Points approximately 10' above Autumn Creek.
28		5350	-	-	170-210	40	S, NE	200	350	1300	(1)
29		6075	SEE REMARKS		no limits	360	SW, NE	925	0	0	(1) On top rounded grassy hill; highest elevation in Blacktail Hills. Nearest trees about 50' away and 10' high. Steepest slopes (approximately 40%) to south.
30		5480	10	260	220-360	140	-	325	220	575	(3) All points <25' from forest margin. Points 4, 5, 6 subject to shading. In shallow vale. Some ponding of water at times.
32		6625	10	130-210	130-250	120	S	825	240	1325	(1) All points <25' from groups of trees. Steeper slopes (up to 40%) above and below station area.
33		5355	5	140	40-270	230	NE	100	130	400	(2) All points <25' from forest margin and subject to shading. Points 6, 10 within forest. Bear grass hummocks abundant.
34		4630	25	270	0-30 180-280	130	SW	175	230	675	(3)
36		5230	(5)	(110)	180-60	240	S, NE	25	120	275	(2) Snow stake in small clearing, subject to shading.
37		5250	(<5)	(120)	100-80	340	S, NE	50	20	150	(5)
38		4840	(5)	(320)	- - G R O U N D W A T E R - - - - - - - - - - -						(5) Near foot of 25% slope. <5' above Skyland Creek.
38A		4840	<5	(220)	- - G R O U N D W A T E R - - - - - - - - - - -						(2) <5' above Skyland Creek.
39		4925	<5	360	260-300 30-50	60	W	200	300	825	(6)
40		4925	<5	(360)	260-300 30-50	60	W	200	300	825	(6)

LEGEND AND DEFINITIONS

Elevation: Feet above mean sea level.

Exposure Sector: That sector of a circle of approximately 1/2 mile radius, centered in the station area, within which there is no land >100' higher than the station. Azimuth Limits = limits of sector, to nearest 10° Az. Size = angular size of sector. Dominant Direction = direction of most pronounced exposure, to nearest of 8 compass points. Lowest Point = difference in elevation between station and lowest point in exposure sector, to nearest 25'.

Shelter Sector: The remaining sector of the circle, within which there is land >100' higher than the station. Size = 360° - exposure sector. Highest Point = difference in elevation between station and highest point in shelter sector, to nearest 25'.

Slope: Mean slope of gradient line through a station point from 5' higher to 5' lower than point. Mean for all points of installation except where variation given, to nearest 5%.

$$\text{Slope} = \frac{\text{Vertical interval}}{\text{Horizontal interval}} \times 100$$

Aspect: Direction of slope at station points. Mean of all points except where variation given, to nearest 10°Az. Azimuth = clockwise angle from true N.

( ): Slope or aspect unsatisfactorily determined because of low gradients or local undulations of surface.

Vegetation and Remarks

(1) In area of scattered trees and small groves.
(2) In clearing or near margin of forest of low (<30') trees.
(3) In clearing or near margin of forest of medium (30-50') trees.
(4) In clearing or near margin of forest of tall (>50') trees.
(5) Within forest or in relatively narrow (<15') passageway in forest of low trees.
(6) Within forest or in relatively narrow (<25') passageway in forest of medium trees.
(7) Within forest or in relatively narrow (<50') passageway in forest of tall trees.

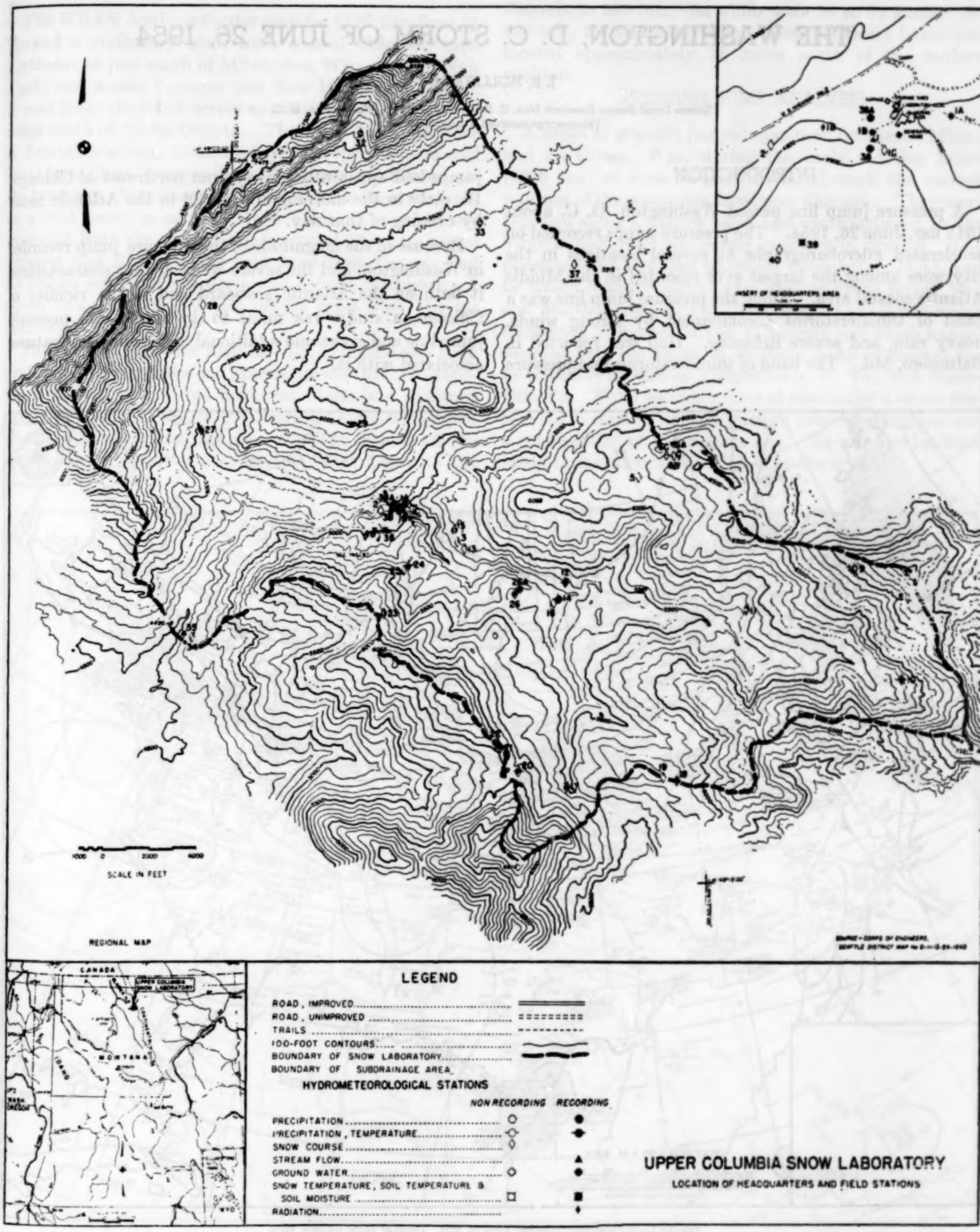
Points: Snow sampling points.

Subject to shading. Subject to tree shading at times during middle part of day. (All points in (5), (6), (7) within 25' of forest margin and subject to shading).

Ground cover in station area mostly grasses and low shrubs except where noted.

Forest = extensive area of moderate to high canopy cover (>30%). Conifers.

#Station A - H is the site of measurements of incident radiation under a forest canopy.


INSERT OF HEADQUARTERS AREA
SCALE IN FEET
REGIONAL MAP
CANADA
UPPER COLUMBIA SNOW LABORATORY
MONTANA
LEGEND
ROAD, IMPROVED
ROAD, UNIMPROVED
TRAILS
100-FOOT CONTOURS
BOUNDARY OF SNOW LABORATORY
BOUNDARY OF SUBDRAINAGE AREA
HYDROMETEOROLOGICAL STATIONS
NON RECORDING
RECORDING
PRECIPITATION
PRECIPITATION, TEMPERATURE
SNOW COURSE
STREAM FLOW
GROUND WATER
SNOW TEMPERATURE, SOIL TEMPERATURE & SOIL MOISTURE
RADIATION
UPPER COLUMBIA SNOW LABORATORY
LOCATION OF HEADQUARTERS AND FIELD STATIONS

THE WASHINGTON, D. C. STORM OF JUNE 26, 1954

J. B. HOLLEYMAN

Severe Local Storms Research Unit, U. S. Weather Bureau, Washington, D. C.

[Manuscript received August 6, 1954]

INTRODUCTION

A pressure jump line passed Washington, D. C. about 1645 EST, June 26, 1954. The pressure jumps recorded on accelerated microbarographs at several locations in the city were among the largest ever recorded in the Middle Atlantic coastal area. Along the pressure jump line was a band of thunderstorms accompanied by strong winds, heavy rain, and severe lightning. Hail was reported in Baltimore, Md. The band of thunderstorms and pressure jumps had apparently moved from northwest of Chicago, Ill. early in the morning of June 26 to the Atlantic coast by evening of that day.

Because of the magnitude of the pressure jump recorded in Washington, and the severe weather that characterized it both on the Atlantic seaboard and in the vicinity of Chicago, a study was made to document this pressure jump line and give some additional meteorological features associated with it.

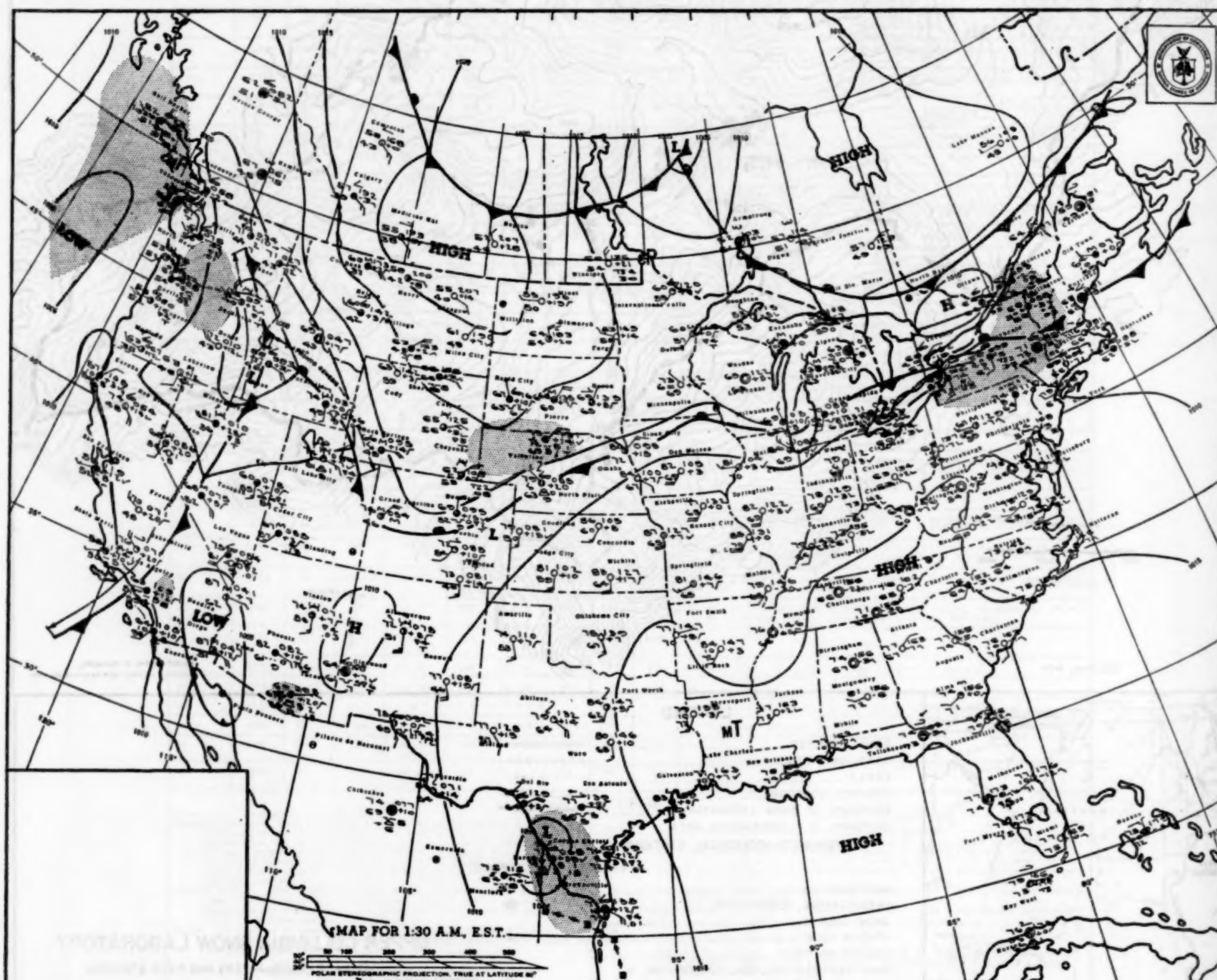


FIGURE 1.—Surface chart 0130 EST, June 26, 1954. Copy of *Daily Weather Map*.

SYNOPTIC SITUATION

The WBAN Analysis Center map for 0130 EST, June 26 showed a stationary front from central Colorado east-northeast to just south of Milwaukee, Wis., through New York, and across Vermont and New Hampshire (fig. 1). A cold front stretched across southern Canada about 150 miles north of North Dakota. There was little difference in frontal positions 12 hours later, except that the cold front from Canada was well into Wisconsin and Minnesota. By 1930 EST, there was a wave on the front (now analyzed as a cold front) in northern New York. The cold front extended from the wave through central Ohio and across Indiana and Illinois. The cold front from Canada had moved to southern Wisconsin and central Michigan. A squall line was indicated just off the coast from Virginia northward to New York.

The 700-mb. chart for 1030 EST (fig. 2) indicated a High centered over Tennessee and Mississippi with a ridge extending northwestward across the Great Plains into Montana and northwestern Canada. There was a deep trough just off the west coast and one somewhat less intense off the east coast. Upper winds from the Great Lakes to the Middle Atlantic coast were from the northwest. From 700 mb. to 500 mb., the winds were 30 to 40 knots. At 850 mb., the stationary front across the Great Lakes was located approximately 75 miles north of the surface position.

PRESSURE JUMP ANALYSIS

A series of pressure jumps began near Rochester, Minn., and La Crosse, Wis., during the early morning hours (0200 EST) of June 26 and moved through the surface position of the stationary front near Chicago. They were reported along a narrow band east-southeastward to the Virginia and Maryland coasts as shown in figure 3. The pressure jump line that traversed Washington, D. C., can be traced with certainty as far west as Front Royal, Va., and Martinsburg, W. Va. The pressure jump line which originated in Wisconsin and Minnesota and which was associated with the seiche in southern Lake Michigan, can be traced as far east as Morgantown, W. Va., and Blairsville, Pa. From considerations of continuity it seems reasonable to assume that the eastern pressure jump line was a continuation of the western one. No attempt has been made to investigate the relation to the seiche.

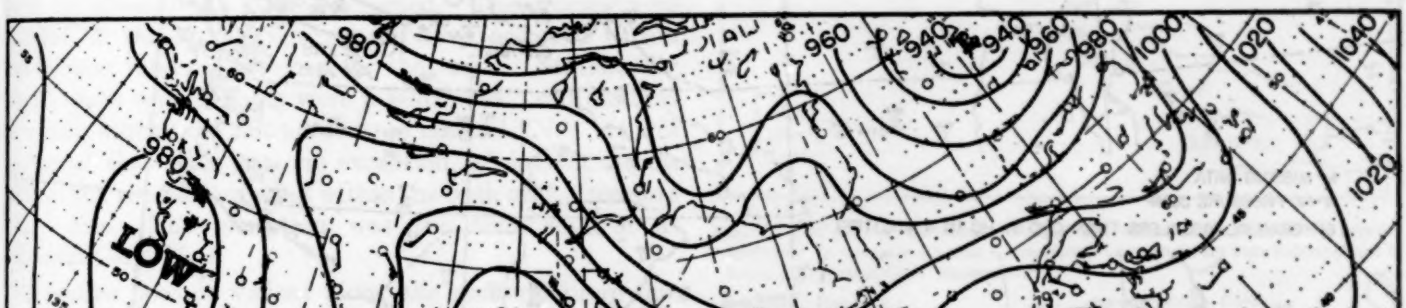


FIGURE 2.—700-mb. chart 1500 GMT (1000 EST), June 26, 1954.

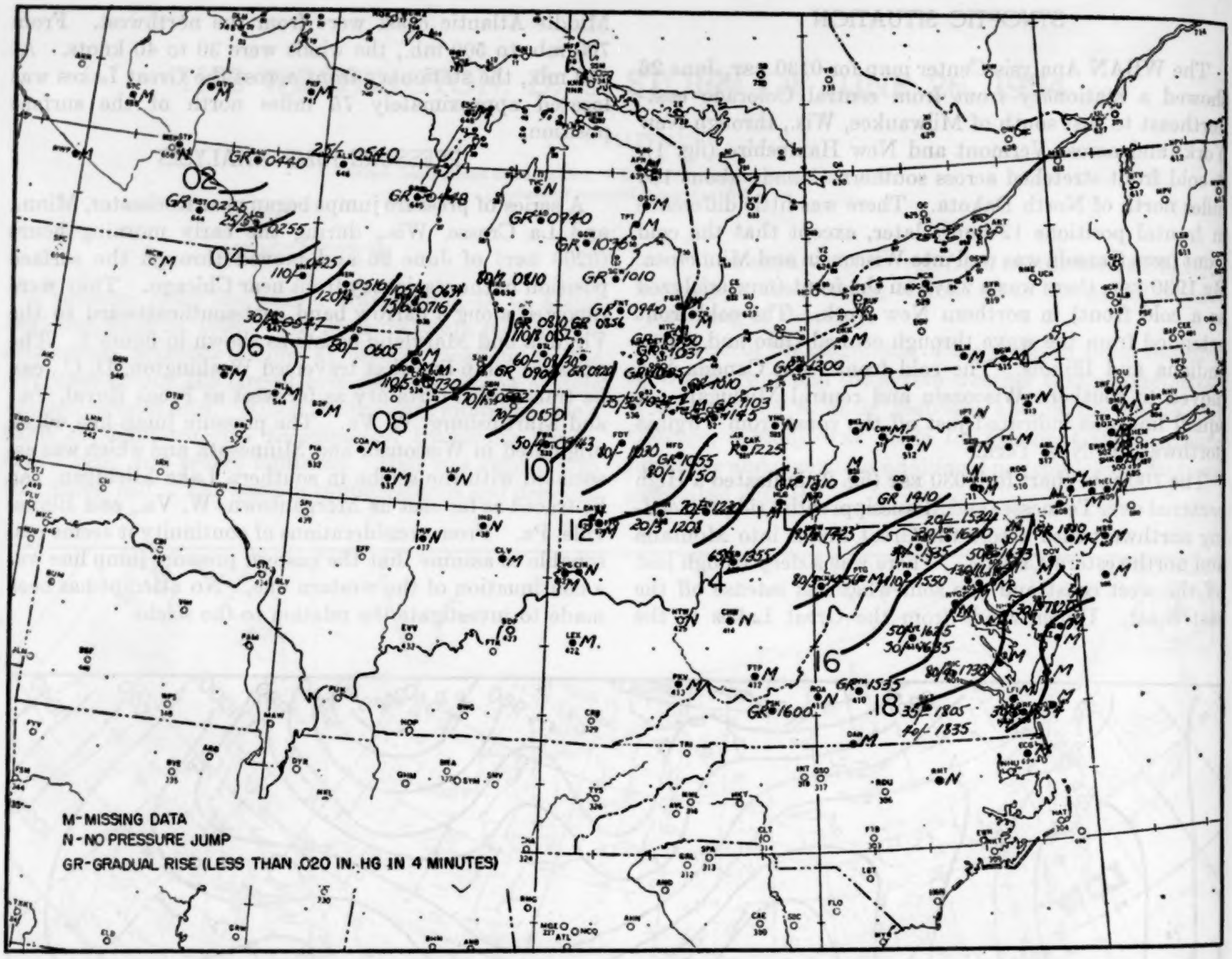


FIGURE 3.—Isochrone analysis of pressure jump line, June 26, 1954. Basic data taken from microbarograms are indicated. To left of station circle is given the ratio of the total pressure rise (in 0.001 in. Hg) to the duration of the rise (in minutes). Dash for duration of rise means reading was from a 4-day trace. To the right of the station circle is the time of beginning of the pressure jump (EST).

Another pressure perturbation, which first made its appearance at Milwaukee, Wis., three-fourths of an hour after the first pressure jump at that station, was identified as a separate system which can be followed as far east as Lansing, Mich., with certainty. This latter perturbation in the Muskegon-Grand Rapids area is not considered here. However, there is a possibility that this line joined the line that originated in western Wisconsin, although data are insufficient to establish this as a fact. The bend that appears in the isochrones in northern Ohio suggests the possibility of two pressure jump lines joining.

Figure 4 illustrates microbarograph traces with significant pressure jumps for stations in the path of the pressure jump line. The horizontal scale is for time. The station call letters are entered beside each trace. The short traces are from 4-day microbarograph sheets, and the other traces are from 12-hour sheets. The time continuity from station to station and the similarity of the pressure rises may be noted, e. g., the steady trace just prior to the sharp rise, the single sharp rise in most cases, and the duration of the higher pressure.

The distance traversed by the pressure jump line from La Crosse, Wis., to the Virginia-Maryland coast was approximately 800 miles in a period of 17 hours, giving an average speed of approximately 47 m. p. h. This distance far exceeds the mean path length of 151–175 miles in the Severe Local Storms Network of the Midwest [1]. The line at the beginning was 60 miles in width (distance between ends of isochrones) and grew to 200 miles in width by the time it passed Washington, D. C., but during most of its history it was approximately 120 miles in width.

SEVERE STORMS

A line of thunderstorms moved with the pressure jump line as it travelled southeastward. The chart in figure 5 illustrates the weather that occurred along the pressure jump line. A broad area was marked off on each side of the path of the pressure perturbation and was divided into zones with time intervals of 6 hours centered on and roughly parallel to the middle isochrone of each zone, with one exception. The exception is the first zone (2300–0500 EST) which is to the west of the first isochrone. The zones were defined to delineate areas of severe local storms and thunderstorms and areas in which these did not occur. Locations of thunderstorms, with or without showers, and severe local storms were obtained from hourly weather sequences and synoptic observations, with the exception of three places. These places were Cumberland and Baltimore, Md., and Washington, D. C. For Cumberland, newspaper clippings were the only source of information. A firsthand description of the storm in Baltimore supplemented the report from the hourly sequences, and in Washington, newspaper reports supplemented the hourly weather report and records at the Central Office.

The legend in figure 5 gives the special set of definitions used to classify the storms reported. The storms were plotted in the appropriate zone if they occurred within the 6-hour interval specified for that zone. Stations for which data were missing were marked "M" and stations at which storms did not occur were marked "N." It will be noted that with but one exception, all known storms within the time interval fell within the path of the pressure jump line. The exception was the thunderstorm at Atlantic City, N. J.

Weather became violent along the pressure jump line shortly after it developed in the Rochester-La Crosse area. At Madison, hail was reported, and at Milwaukee, heavy rain fell. As the line moved across Columbus, Ohio, strong winds with gusts to 52 m. p. h. were reported. Cumberland, Md., which was in the path of the pressure jump line, had a violent wind storm, accompanied by rain and lightning. Descriptions of the storm, such as "near twister," give reason to consider the storm as a possible tornado, perhaps not quite touching the ground.

Violent weather continued to accompany the pressure jump line as it moved southeastward. A micro-network of three accelerated microbarographs in the metropolitan area of Washington, D. C., established by the Severe Local Storms Research Unit gave a detailed picture of the pressure jump line as it passed the city. All three instruments of the network and the instrument at the National Airport had pressure rises of .090 in. Hg or more. At the Central Office, where one of the accelerated microbarographs of the network is located, a record of events was made by other instruments along with the microbarograph. Figure 6 illustrates the sudden changes recorded by the

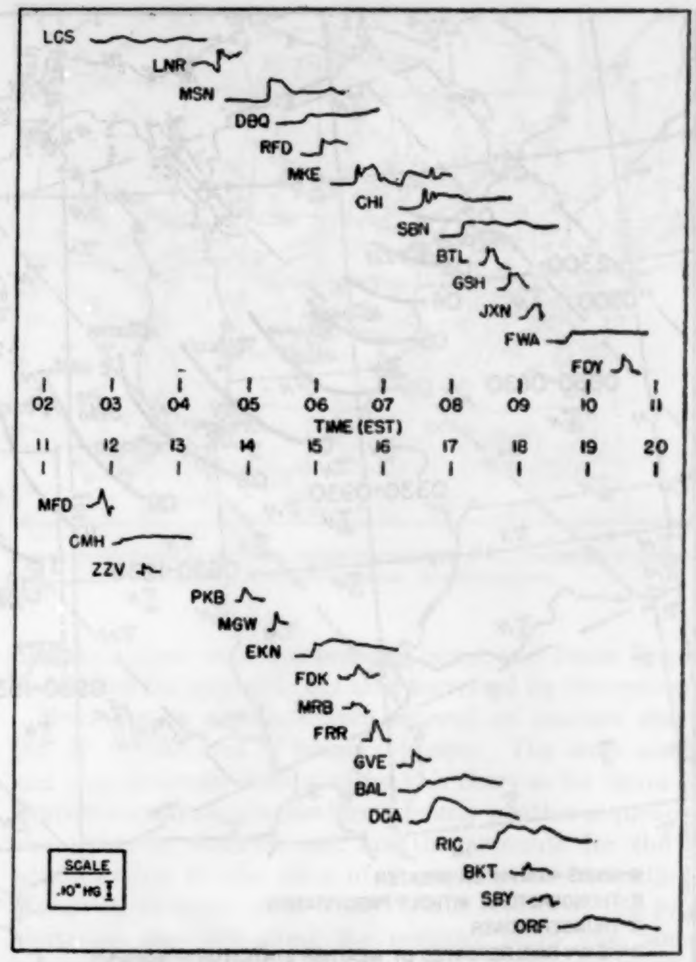


FIGURE 4.—Microbarograph traces with significant pressure jumps along path of pressure jump line. Short traces are from 4-day charts. Long traces are from 12-hour charts to which time scale applies. Stations are:

LCS—La Crosse, Wis.
LNR—Lone Rock, Wis.
MSN—Madison, Wis.
DBQ—Dubuque, Iowa.
RFD—Rockford, Ill.
MKE—Milwaukee, Wis.
CHI—Chicago, Ill.
SBN—South Bend, Ind.
BTL—Battle Creek, Mich.
GSH—Goshen, Ind.
JXN—Jackson, Mich.
FWA—Fort Wayne, Ind.
FDY—Findlay, Ohio.
MFD—Mansfield, Ohio.
CMH—Columbus, Ohio.
ZZV—Zanesville, Ohio.
PKB—Parkersburg, W. Va.
MGW—Morgantown, W. Va.
EKN—Elkins, W. Va.
FDK—Frederick, Md.
MRB—Martinsburg, W. Va.
FRR—Front Royal, Va.
GVE—Gordonsville, Va.
BAL—Baltimore, Md.
DCA—Washington, D. C.
RIC—Richmond, Va.
BKT—Blackstone, Va.
SBY—Salisbury, Md.
ORF—Norfolk, Va.

accelerated microbarograph, triple register (precipitation and wind speed and direction), and hygrothermograph. The pressure rose .130 in. Hg (4.4 mb.) in 11 minutes, and in the same length of time the temperature dropped from 94° F. to 72° F., a change of 22°. Two hours before the storm, the temperature had been 99° F. At the time the temperature dropped sharply, the relative humidity rose from 35 percent to 90 percent. Prior to the pressure jump, the wind was southwest at 10 m. p. h. With a slight rise in pressure a few minutes before the jump, the

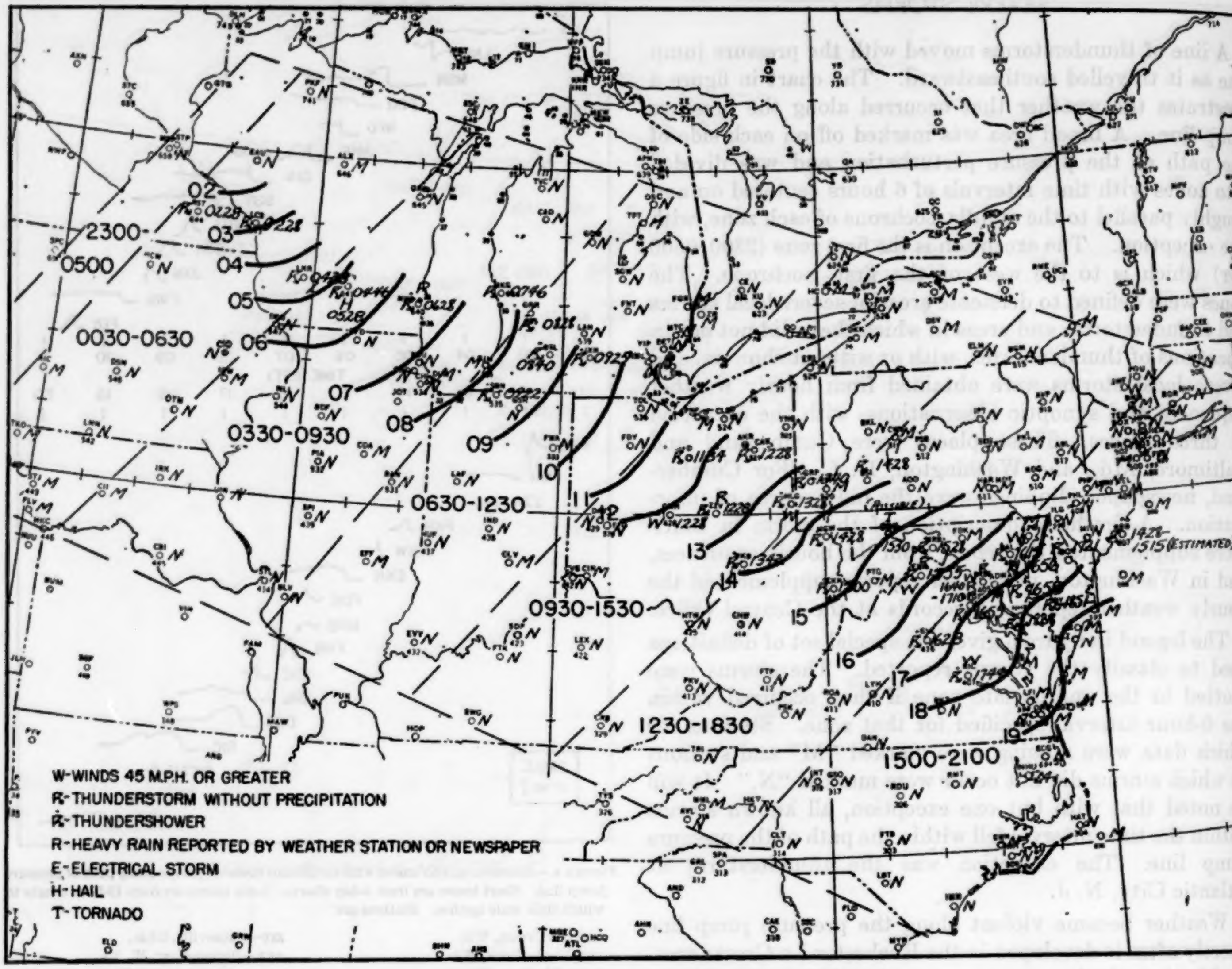


FIGURE 5.—Severe local storms along pressure jump line. All times EST.

wind shifted to west at 10 m. p. h. and then to northwest with the large rise. Within a minute after the beginning of the jump, the wind was northwest at 50 m. p. h. At the National Airport, where the pressure jump began at 1643 EST, precipitation was reported as beginning at 1635. At the Central Office, heavy precipitation began about 10 minutes after the onset of the pressure jump. In the following 10-minute period, 0.51 inch of rain fell. Four minutes later, the total amounted to 0.60 inch.

In the metropolitan area of Washington, D. C., strong winds, clocked at a maximum of 66 m. p. h. at the Weather Bureau at National Airport, did considerable damage. Trees were blown down, blocking roads in nearby Virginia. At least one house was unroofed, and power lines at several points were blown down. The heavy rain caused a small flash flood in one part of the city. In nearby Maryland, several houses were reported struck by lightning.

In Baltimore, where the squall line arrived a few minutes earlier than in Washington, large hailstones fell in the northeastern section of the city, some described as being as large as baseballs.

TEMPERATURE AND PRECIPITATION DISTRIBUTION

Maximum temperatures for June 26 along the path swept by the pressure jump line and surrounding areas were plotted (see fig. 7). The temperature pattern in the western part of the area has little meaning in relation to the pressure jump line, since the line moved through during the morning. However, east of the Appalachian Mountains it may be noted that the largest pressure jumps occurred where the maximum temperatures were highest. Washington, D. C., and Front Royal, Va., both had maximum temperatures of 100° F. Washington

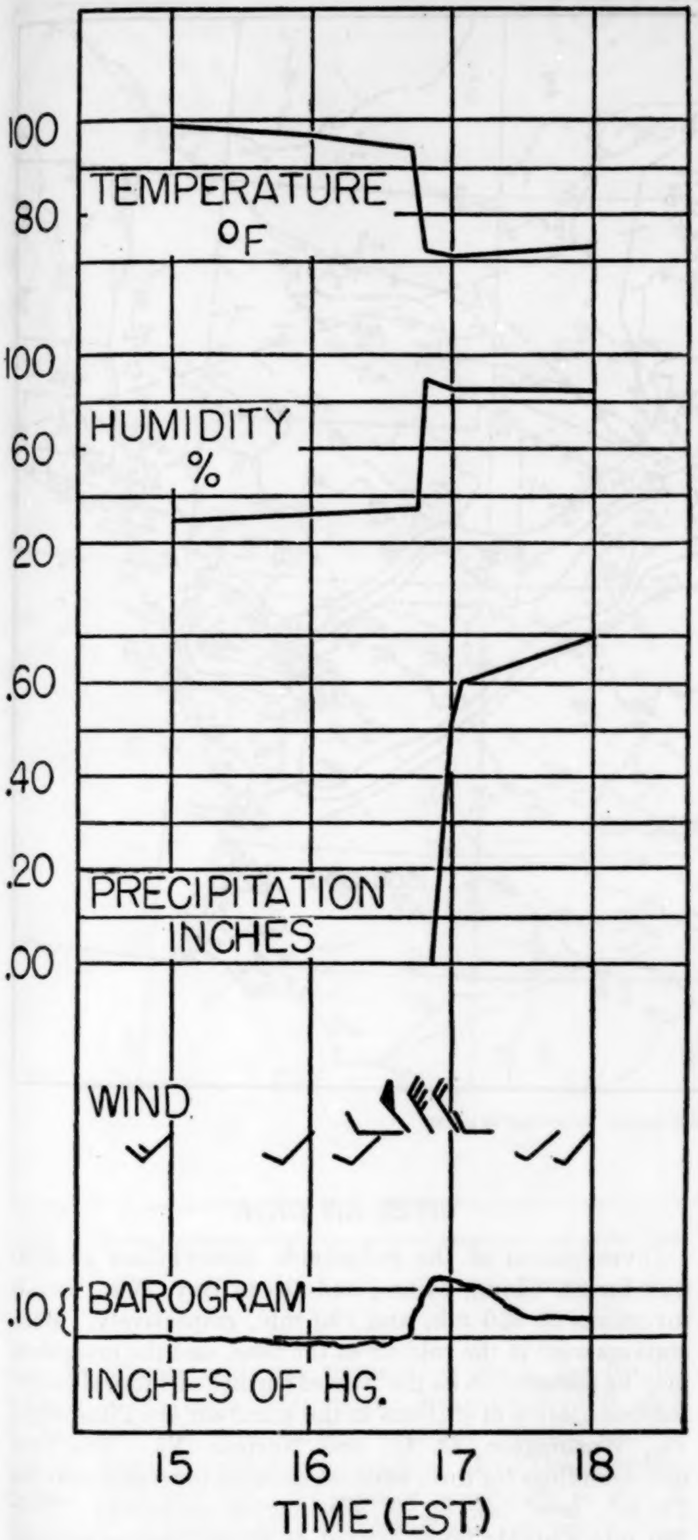


FIGURE 6.—Records from hygrothermograph, triple register, and accelerated microbarograph, Weather Bureau Central Office, Washington, D. C., June 26, 1954.

FIGURE 7.—Isotherms of maximum surface temperatures (° F.) along path of pressure jump line and surrounding areas. M=data missing.

had the highest recorded pressure jump, and Front Royal had one of the largest in the area traversed by the system.

Precipitation amounts were entered on another chart (fig. 8) for the area of pressure jumps. The same zones and time intervals were used for this chart as for figure 5. Precipitation data, obtained from hourly weather sequences and synoptic observations, are the amounts for the 6 hours ending at the time of the synoptic observation. However, in most cases these figures represent the precipitation that fell along the pressure jump line, since precipitation was not widespread at any time during the 6-hour interval except coincident with the pressure perturbation. Two areas of maximum rainfall existed, one centered around Milwaukee, Wis., and the other at Washington, D. C. A secondary maximum might be said to exist near Zanesville, Ohio. The two maxima lie along the northern part of the isochrones and the secondary maximum lies at the southern end of the isochrones. There is no ready explanation for the lack of or small amount of precipitation in the region between Chicago and Fort Wayne, Ind. Diurnal effects may have minimized the influence of the pressure jumps on the atmosphere. Maximum rainfall did not occur at all points of large pressure rises, but examination of figures 3 and 8 will show that the greatest amounts of rainfall coincided with areas of maximum pressure rises.

It is of significance that most of the precipitation fell within the boundaries of the path traversed by the pressure jump line. The traces of rainfall that fell in southern Michigan outside the path may be attributed to the second pressure jump line that was first detected at Milwaukee. The trace of precipitation at Cadillac was drizzle. At Atlantic City, N. J., rain occurred approximately four hours before the pressure jump line was nearest the station.

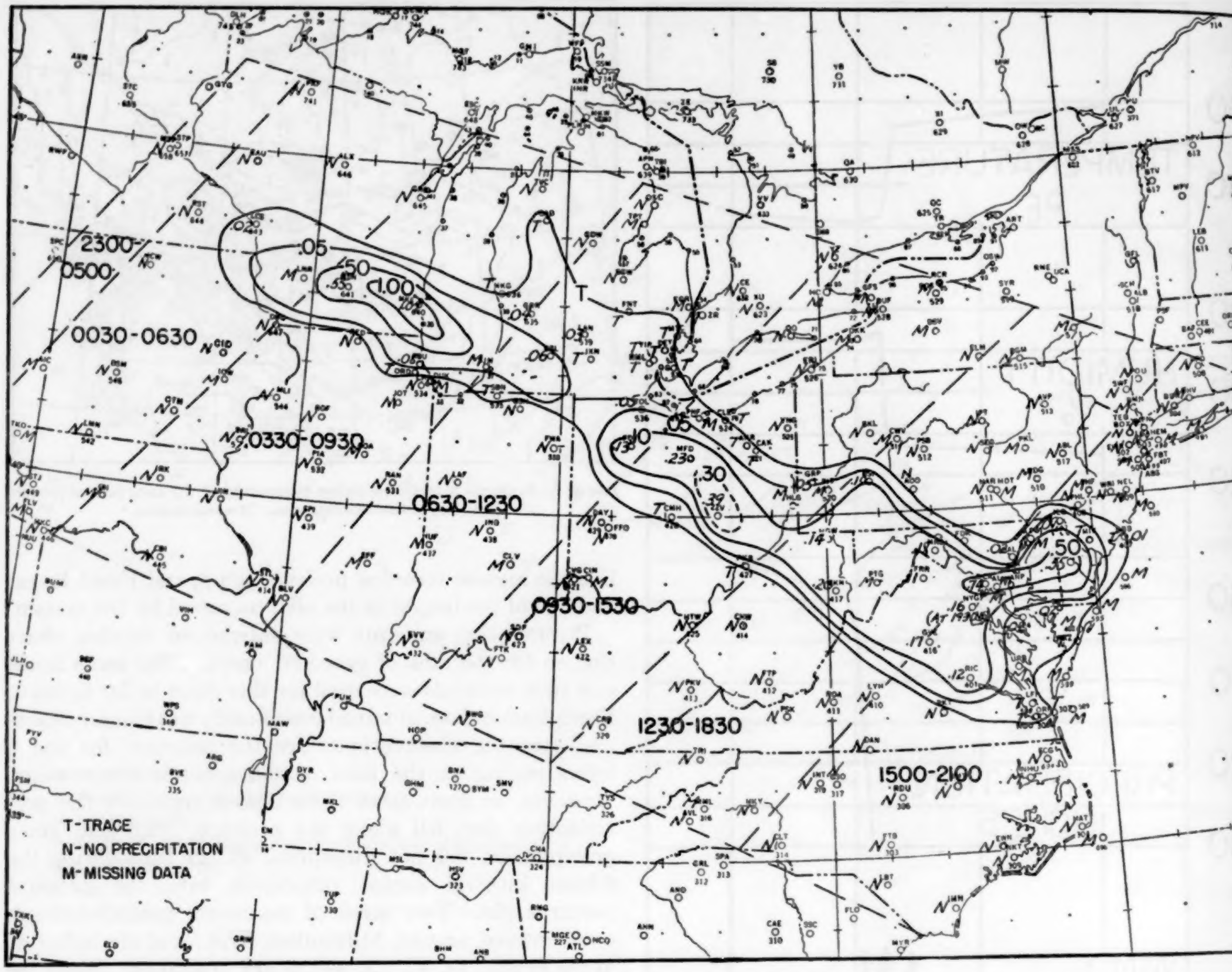


FIGURE 8.—Precipitation area along path of pressure jump line. Precipitation in inches. Time intervals in EST.

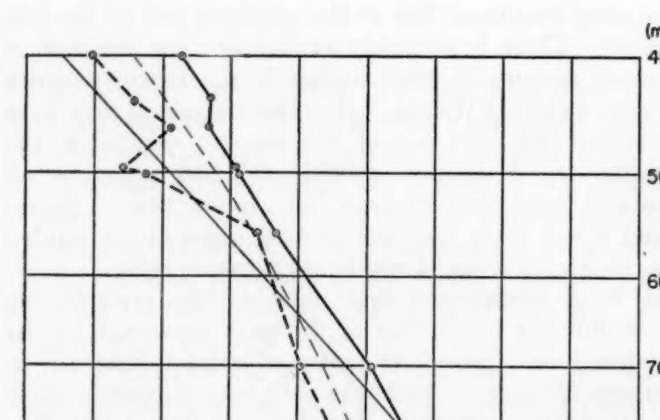


FIGURE 9.—Upper air sounding for Washington, D. C., 1030 EST, June 26, 1954. The temperature curve is represented by solid line; dew point curve by dashed line.

UPPER AIR DATA

Investigation of the radiosonde observations at 0300 GMT for St. Cloud, Minn., and Green Bay, Wis., reveals inversions at 850 mb. and 790 mb., respectively. Both stations were in the cold air at the time, and the inversions may be assumed to be the frontal surface at those stations. Representative of stations in the warm air are Pittsburgh, Pa., Washington, D. C., and Norfolk, Va. The 1500 GMT soundings for these stations show an inversion near the 850-mb. level (see fig. 9, Washington sounding). Near 500 mb. a stable layer existed at all radiosonde stations which were checked. From the data it becomes evident that the 850-mb. level and the 500-mb. level were the only surfaces along which an atmospheric gravity wave could have been propagated for any great distance [2]. One possible interpretation is that a gravity wave formed

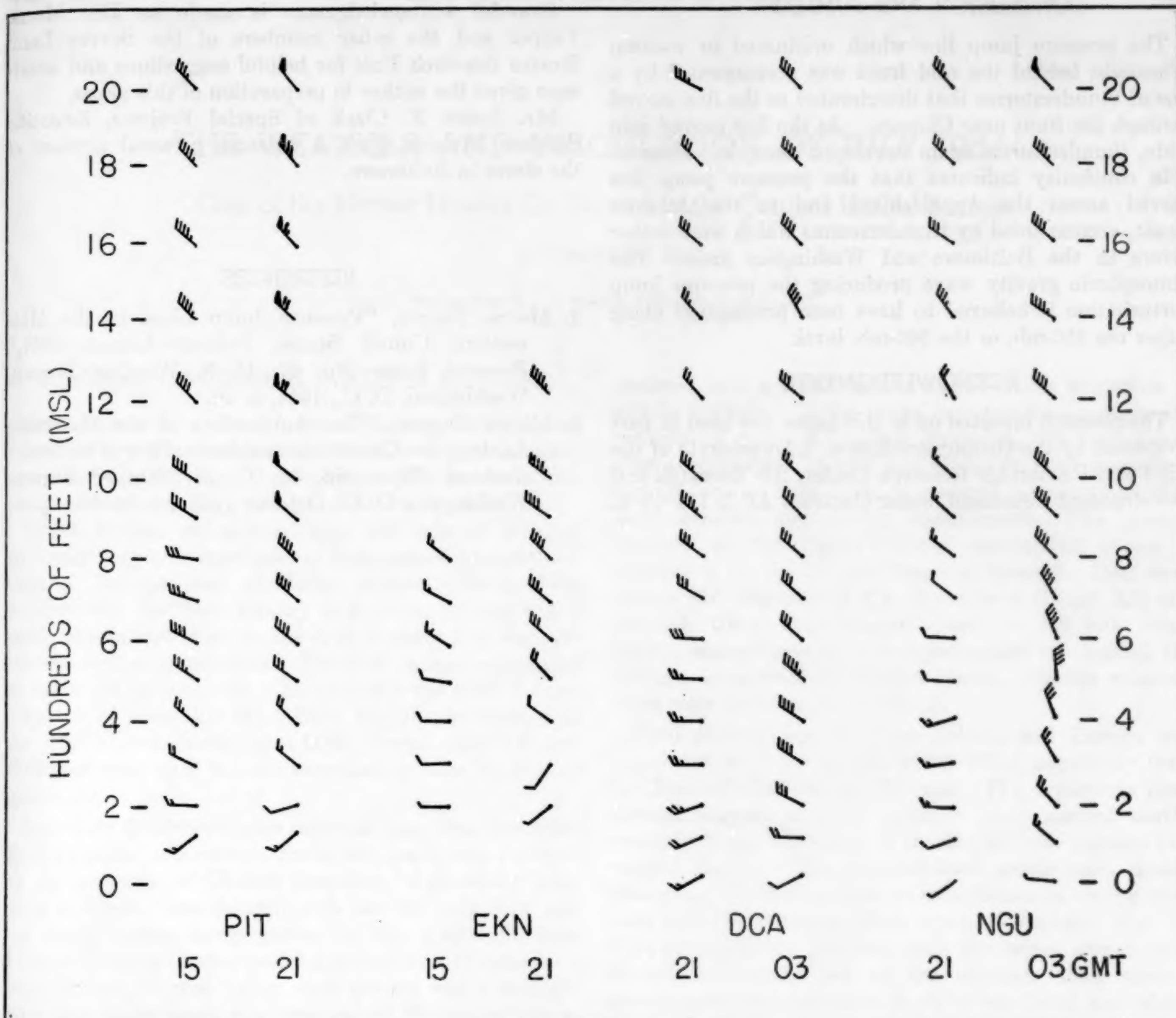


FIGURE 10.—Winds aloft before and after passage of the pressure jump line at Pittsburgh, Pa. (PIT), Elkins, W. Va. (EKN), Washington, D. C. (DCA), and Norfolk, Va. (NGU) (Navy Station).

near La Crosse and was propagated along the frontal surface or inversion (850 mb.). Near Chicago it may be assumed the perturbation somehow started passing into the warm air and was propagated along the inversion surface near 850 mb. The other possibility is that a gravity wave formed near La Crosse and was propagated along the stable layer near 500 mb. Although previous investigations concerning gravity waves in the atmosphere favor the idea of propagation at lower levels, the possibility of a gravity wave at 500 mb. should not be overlooked, especially since the inversion near 850 mb. at Washington had disappeared by 2100 GMT due to surface heating. It is not known whether or not the inversion at other stations had disappeared since the Washington sounding for 2100 GMT is the only one available in the area. Some remnant of the inversion near the 850-mb. level may have existed over much of the area from the Appalachians eastward during the afternoon, although surface temperatures at many points indicated an almost dry adiabatic lapse rate to 850 mb. and above. Examination of the winds aloft failed to reveal any particular level of wind shear which would indicate a discontinuity in the atmosphere along which a gravity wave could be propagated.

From figure 10 it can be seen that winds at most of the levels increased after the pressure jump line passed a station. However, winds above 10,000 feet showed a tendency to increase more than those below. The pressure jump line was located beneath the narrow band of jet winds at upper levels.

CONCLUSION AND SUMMARY

The pressure jump line which originated in western Wisconsin behind the cold front was accompanied by a line of thunderstorms that deteriorated as the line moved through the front near Chicago. As the line moved into Ohio, thunderstorms again developed along it. Reasonable continuity indicates that the pressure jump line moved across the Appalachians and to the Atlantic Coast, accompanied by thunderstorms which were rather severe in the Baltimore and Washington areas. The atmospheric gravity wave producing the pressure jump perturbation is believed to have been propagated along either the 850-mb. or the 500-mb. level.

ACKNOWLEDGMENTS

The research reported on in this paper has been in part sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract AF R 114-49-4.

Grateful acknowledgment is made to Dr. Morris Tepper and the other members of the Severe Local Storms Research Unit for helpful suggestions and assistance given the author in preparation of this paper.

Mr. James F. Cizek of Special Projects, Scientific Services Division, gave a welcome personal account of the storm in Baltimore.

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THE WEATHER AND CIRCULATION OF JULY 1954[1]

One of the Hottest Months On Record in the Central United States

H. F. HAWKINS, JR.

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

SUMMARY OF UNUSUAL WEATHER FEATURES

One of the most striking facets of the circulation during July 1954 was the persistence of weather type over many regions of the Northern Hemisphere. The results of this persistence were widely noted and deserve mention.

Great Britain experienced cold and stormy weather with only very brief interludes of more pleasant conditions. Central Europe was similarly plagued. Since June weather also had been stormy in Europe, 70 continuous hours of rain and snow on the Alps in early July sent the Danube well over its banks. This flood was characterized as the worst in centuries. At one time the river flooded a stretch of some 300 miles from Vienna upstream. As the crest passed downstream both Vienna (July 14) and Budapest were hard hit and surrounding farm lands were inundated.

Late July floods were also reported from Iran and from East Pakistan and eastern India but these were dwarfed by the accounts of Chinese disasters. Apparently wide areas of China were deluged with rain in early July and the rising waters congregating in the 3,100-mile long Yangtze River left widespread destruction. Hundreds of miles of the Yangtze Valley were flooded and a new all-time high water mark was recorded at Wuhan as late as mid-August.

In contrast to the cold and floods so prominent elsewhere, the United States was troubled by heat and drought. Their greatest effects were felt in the 6-State area; Nebraska, Kansas, Oklahoma, Louisiana, Missouri, and Arkansas, as well as northern and western portions of Texas. Above normal temperatures were both persistent and extreme—on the 14th St. Louis recorded 115° F. and East St. Louis 117° F., the highest temperature ever recorded on or east of the Mississippi River. Deficient rainfall combined with searing heat compounded the drought conditions remaining from June [1].

THE HEMISPHERIC CIRCULATION

Figure 1 shows the mean 700-mb. flow pattern for July. At polar latitudes there were two troughs present which resolved into a five-trough pattern in the westerlies of middle latitude. Of the ridges between these troughs the continental ridges (Canadian, Eurasian, and East-Asian) were accompanied by well-marked height departures from normal (dashed lines in fig. 1) centered farther north than their Atlantic and Pacific counterparts. The general warmth of the higher-latitude continental ridges is attested to by the 200-mb. ridges of figure 2. Over both oceans the maritime Highs of sea level (Chart XI) and 700 mb. were conspicuously absent at 200 mb. Contrarily, anticyclonic conditions intensified up through the 200-mb. level over the United States. Similar relationships were noted in July 1953 [2].

Cold stormy weather over Britain and Europe was associated with the trough which tilted negatively from the Icelandic Low to the Balkans. The departures from normal suggest a much stronger than normal northwesterly (cyclonic) influx of marine air into western and central Europe. The Chinese flood seems most closely related to the deeper than normal monsoon trough over Asia and the blocking High west of Sakhalin (fig. 1). This configuration, together with the minor trough over Korea, apparently led to the stronger than normal southeasterly components (both at sea level and aloft) north of 35° N. and stronger southwesterly components south of 35° N. These conditions could be regarded as a concentrated localization of the normal monsoon circulation.

The upper level circulation affecting North America was of the most frequent summer type, i. e., a trough off either coast with a warm High over the United States (most recent exception was July 1950). July 1954 was distinguished, however, by a number of features: (1) the abnormal strength of the troughs, (2) the Canadian ridge which was farther east and stronger than normal (+260 feet), and (3) the persistence of this pattern and its cumulative effect.

CIRCULATION PATTERN OVER THE UNITED STATES

At 700 mb. the dominating circulation feature was the upper level High centered over southern Missouri. This anticyclone was stronger than normal (+80 feet) and

[1] See Charts I-XV following p. 217 for analyzed climatological data for the month.

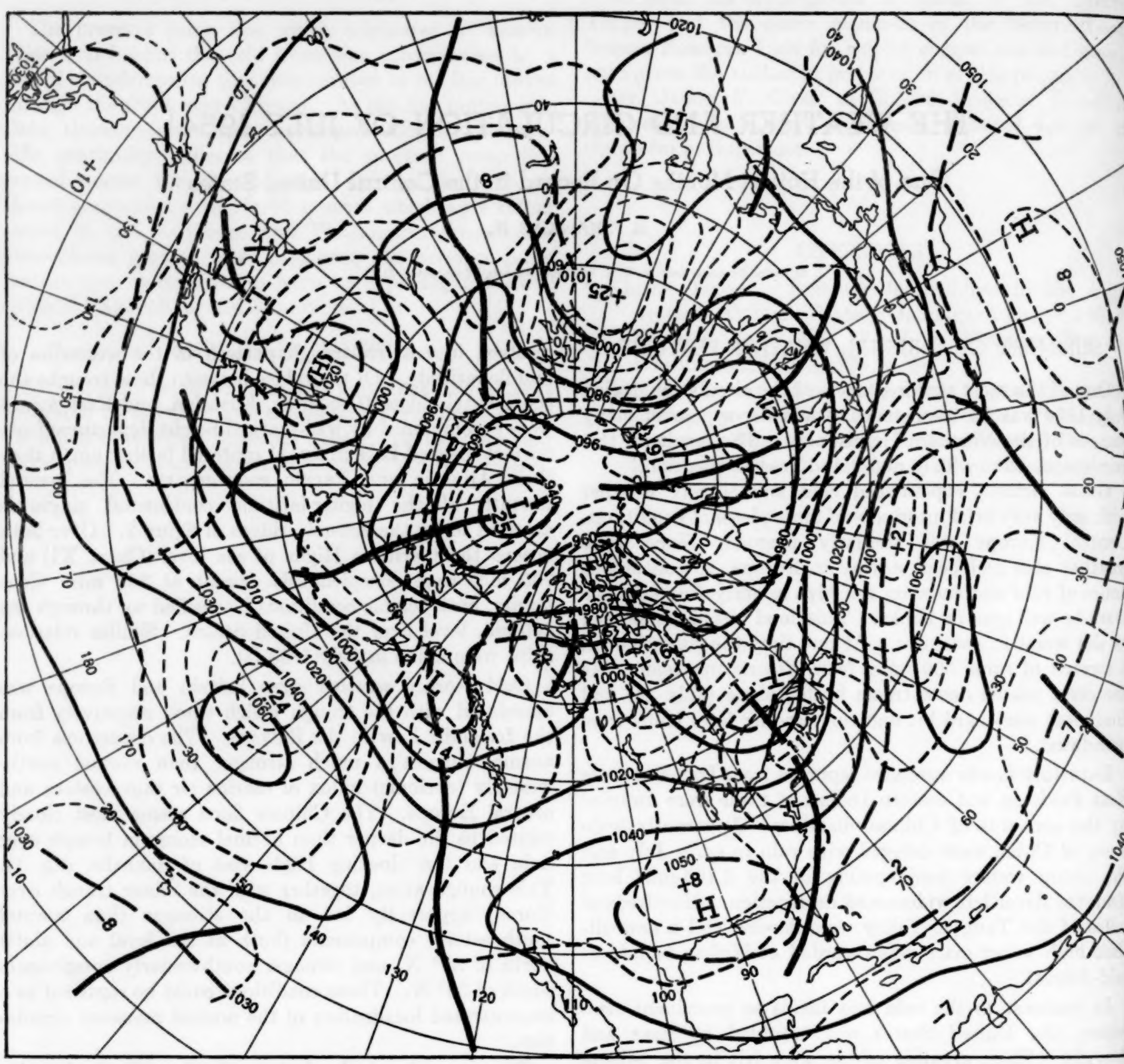


FIGURE 1.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for June 29—July 28, 1954. Anticyclonic circulation over the United States with a trough off either coast appeared to be a stable regime with hemispheric interrelations which prevailed most of the month.

(characteristic of the 1954 summer) had a well-defined east-west axis of above normal heights which was centered about 35° N. The High seemed even stronger at higher levels (fig. 2), as previously mentioned, but was only weakly reflected at sea level. In fact, sea level pressures were below normal (Chart XI, inset)—an obvious effect of a warmer than normal troposphere. (See also June 1954, [1].) Figure 3 affords a comparison of the relative vorticities at 700 and 200 mb. The strengthening of the anticyclonic and cyclonic vorticity centers at higher levels is quite common but not always so well marked. It may be interesting to note that although the maritime Highs (Chart XI) almost disappeared at 200 mb. (fig. 2), the shear to the right of the "mean jet" was associated with the maintenance of anticyclonic vorticities throughout the troposphere.

This "jet" (fig. 2) along the Canadian-United States border was somewhat stronger than normal but very close to its normal position. The contribution of such a jet to the maintenance of an upper level High to its right (over the United States) has not been thoroughly investigated. However, its role in long-sustained circulation patterns where persistent fields of divergence prevail through deep atmospheric layers appears to be an impor-

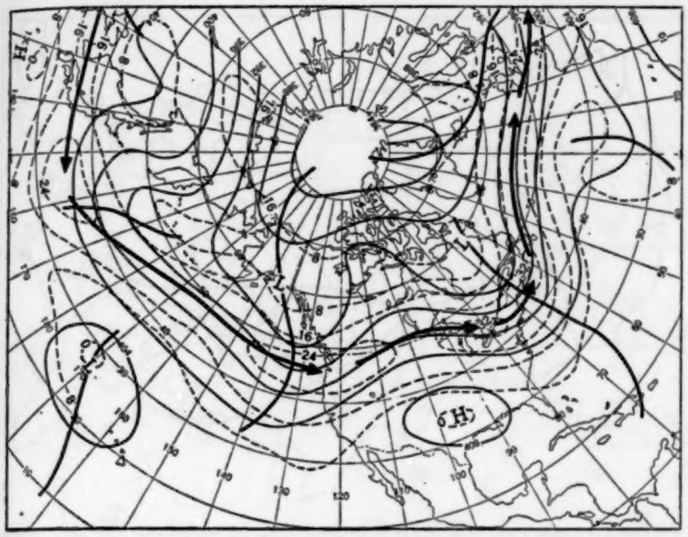


FIGURE 2.—Mean 200-mb. contours (in hundreds of feet) and isotachs (dashed, in meters per second) for June 29-July 28, 1954. Intense "jet" along United States-Canadian border was stronger than normal. Note United States High (fig. 1) intensified aloft while maritime Highs almost disappeared.

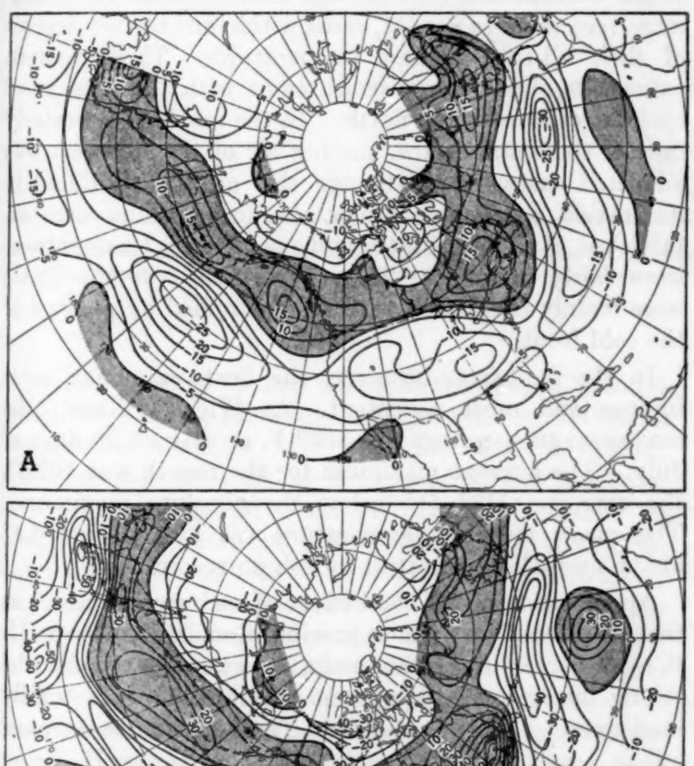


FIGURE 3.—Vertical component of mean relative geostrophic vorticity June 29-July 28, 1954. (A) 700 mb. Isopleths are drawn for units of 5×10^{-6} sec^{-1}. (B) 200 mb. Isopleths are drawn for units of 10×10^{-6} sec^{-1} Anticyclonic vorticity increased markedly aloft over the continental anticyclone and increased more slowly over the maritime Highs which have almost disappeared at 200 mb. (fig. 2).

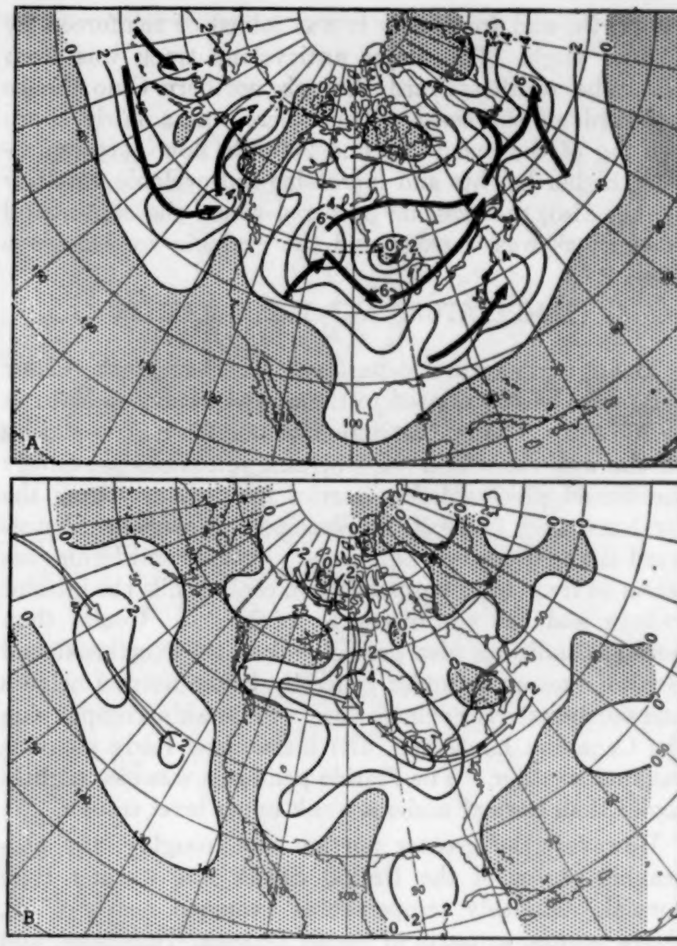


FIGURE 4.—Frequency of cyclone passages (A) and anticyclone passages (B) (within 5° squares at 45° N.) during July 1954. Unusual number of cyclones occurred to right of upper level "mean jet", however, major cyclone track was well marked in southern Canada. Cool Canadian Highs maintained mild summer weather over northeastern United States.

tant one. Curiously enough, quite a few sea level cyclonic systems (fig. 4A) occurred to the right of the "mean jet" under the area of anticyclonic shear aloft. This was in marked contrast to the relationship more frequently noted in this series of articles. Inspection, however, reveals that these were weak Lows on, or associated with, the trailing fronts of primary systems which were travelling eastward through Canada north of the daily (and mean) jet. The formation of such closed centers may well be associated with the warmth experienced in the United States and with an exaggerated sea level intensification of the southern end of the migratory westerly perturbations. In general, the primary track of significant storms lay, as usual, to the left of the mean jet and bore a normal relationship to upper level steering currents.

Stronger than normal westerlies off the United States west coast produced frequent intrusions of cool Pacific air masses. These invasions did not result in the appearance of a path of anticyclones across the Pacific coast in figure 4B because only closed high centers are tracked in Chart IX. Usually the Pacific surge formed a closed center first over the Plateau or a mountainous area to

the north, and frequently it was joined or reinforced by a polar High. The major anticyclone track was from Manitoba southeastward through northern Ohio thence eastward off the coast. Thus there was a fairly sharp crossing of the mean 700 and 200-mb. flow patterns toward higher heights and increasing anticyclonic vorticity aloft. Also, the crossing occurred where the continental "mean jet" was weakest and the cyclonic vorticity was least.

TEMPERATURE AND PRECIPITATION

Mean temperature departures for the month (Chart I–B) were closely related to the mean circulation features at 700 mb. The mid-latitude cyclonic fetch of westerlies off the west coast and the maritime intrusions previously mentioned effected below normal temperatures from the far Northwest (−4° F. in Washington) south-southeastward through eastern California. Coastal California was warm as frequently happens when cool air fills the interior valleys and the sea breeze is minimized. Cooler than normal conditions also prevailed over the Northeast and Great Lakes areas under generally below normal heights and northwesterly cyclonic flow. Polar air accompanying the Canadian Highs (fig. 4B) maintained fairly pleasant summer weather. The Florida peninsula was also slightly cooler than normal under a weak upper level trough.

However, the greater portion and, roughly, the geographic center of the United States was warmer than normal. Monthly temperatures averaged nearly 6° F. above normal in parts of South Dakota, Tennessee, and Texas. Southeastern Kansas and northeastern Oklahoma averaged 8° above normal with adjacent areas of Kansas, Missouri, Oklahoma, and Arkansas more than 6° above normal. Thus the warm upper level anticyclone and above normal heights provided a shield against prolonged or pronounced cold air intrusions while affording optimum opportunity for insolation.

Figure 5 shows the peregrinations of the 700-mb. 5-day mean anticyclone during July. In June the mean High was central over Georgia-Alabama, but it began to retrograde at the end of the month [1]. Its continued retrogression during July was one of the notable features of the month. The upper level anticyclone moved slowly westward during the first half of July. It dominated the lower Mississippi Valley continuously until rapid and more irregular movements became evident on the 19th. These culminated in a splitting of the mean High at the end of the month. While it prevailed over the central United States extreme temperatures were observed over fairly wide areas.

Figure 6 shows the absolute maximum temperature (upper numeral) of record through 1953; the lower numerals are the July 1954 maxima. Thus, Sheridan, Wyo., tied its record maximum of 106° F.; Caspar, Wyo., set a new record of 104°; etc. Table 1 shows (from currently available records) where and when absolute maxima were broken.

FIGURE 5.—Position and intensity of 5-day mean High (at 700 mb.) for July 1954. Dates (upper numerals) are mid-days of overlapping 5-day periods; lower numerals are intensity in tens of feet. Slow retrograde movement of anticyclone and its domination of mid-continent area are evident for first half-month.

Inspection of figure 6 also reveals that many stations of the Central and East Central States, where new maximum records were not set, came within one or two degrees of their all-time highest temperatures. These eastern extensions of extreme warmth came with the passage of cyclonic centers to the north. In the quickened westerly flow of the warm sector, the hot air of the Midwest was advected eastward. Although this air was modified in its travels, a number of new absolute maxima were established in eastern States and near record temperatures were fairly common. These conditions (in the East) were mainly temporary with relief supplied by passage of the cold front.

In the Midwest, however, the heat was both more intense and most persistent. At Wichita, Kans., the maximum temperature was 100° F. or over on 20 days of July. The average maximum for the month was 102.6°, the extreme, 113° (1° below the absolute maximum). The mean monthly temperature was 89.3°, some 8.4° above normal—the hottest month on record!

Appreciation of the total effect of such temperatures as these is incomplete without precipitation data. Chart III, the July precipitation anomaly, indicates that under the strong upper level anticyclone precipitation was totally inadequate. From west central Texas east-northeastward

TABLE 1.—*Value and date of new absolute maximum temperature records established during July 1954*

Station	Temperature ° F.	Date	Station	Temperature ° F.	Date
Casper, Wyo	104	12	Columbia, Mo	113	14
Colorado Springs, Colo	100	13	St. Louis, Mo	115	14
North Platte, Nebr	112	11	Springfield, Ill	112	14
Norfolk, Nebr	113	11	Youngstown, Ohio	100	14
Tulsa, Okla	112	14	Huntington, W. Va	105	14
Dallas, Tex	111	25	Greensboro, N. C	102	14
Austin, Tex	109	26	Frederick, Md	102	31
Springfield, Mo	113	12	Wilmington, Del	102	31

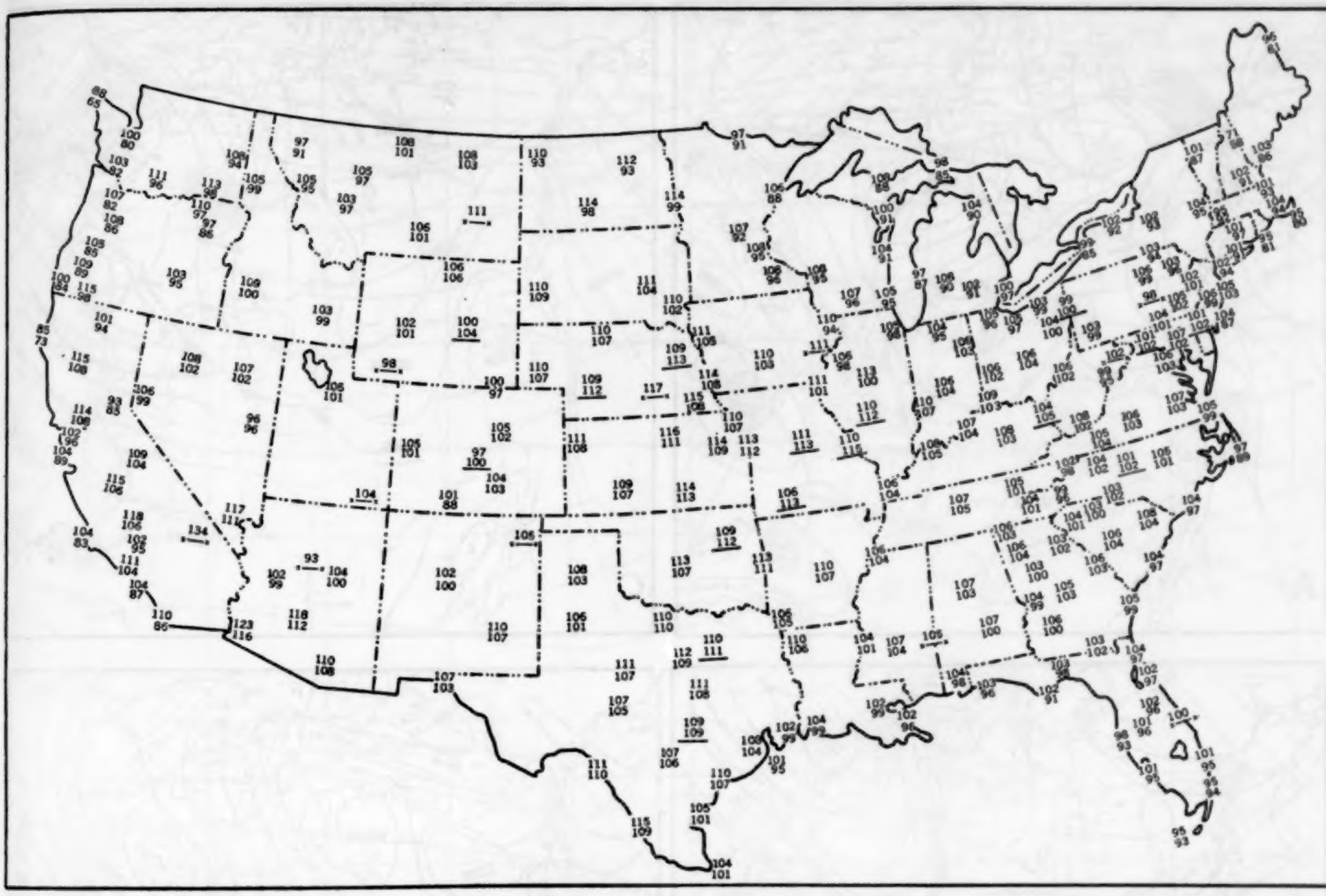


FIGURE 6.—All-time maximum temperatures of record through 1953 (upper numerals) and maximum observed during July 1954 (lower numerals) in ° F. New absolute maxima are underlined; x—x indicates data not available. Note many new maxima and approach to all time records from the Rocky Mountain States to the east coast.

to western Tennessee and north-northeastward through Oklahoma, Kansas, Missouri, Iowa, and eastern Nebraska precipitation amounts were less than half of normal. Oklahoma received only 24 percent of normal precipitation, Arkansas and Missouri 39 percent, Nebraska 42 percent, Iowa 48 percent, Kansas 49 percent, and northwestern Texas from 0 to 25 percent. As can be readily imagined, the combination of record or near record temperatures and strongly deficient precipitation brought about major drought conditions. There is not currently available any total index of drought conditions which measures the combined effect of temperature and precipitation. However, soil and plant moisture losses with temperatures over 100° F. and appreciable air movement were enormous.

Thus July brought the persistence and expansion of a drought regime which began to affect the central United States during late June [1]. The result of this sequence was extension of the federally recognized drought disaster area eligible for federal aid. To Colorado, Wyoming, New Mexico (where spring and early summer had been dry, and July precipitation was insufficient) and Texas (where drought continued) were added Oklahoma and Missouri. Six other States appealed for such aid: Kansas, Arkansas, Tennessee, Alabama, Georgia, and Kentucky. Drought conditions also threatened a number of eastern States. From the Carolinas to New York precipitation was generally less than normal (New Jersey received only 36 percent of normal July precipitation) and in many eastern localities the drought was severe.

The pattern of appreciable precipitation (Chart III) can be reasonably associated with the mean circulation. In the far Southwest (Arizona, Utah) shower activity was more marked than usual in the western moist tongue. These moist air injections were propagated northeastward and rains were noted in Colorado, western Nebraska, and the Dakotas. Propelled by the circulation around the upper level anticyclone this moisture contributed to above normal precipitation in Minnesota, Wisconsin, Illinois, Indiana, Michigan, and Ohio. These rains were of the frontal and air mass shower type with instability usually released by the influence of westerly perturbations which were centered farther north, or by overrunning of the cool Highs. Precipitation was also noted from eastern Ohio southward along the Appalachians as the moisture continued its trajectory around the upper level High. In Florida, precipitation was above normal under the weak trough aloft, and the immediate Gulf Coast from Louisiana

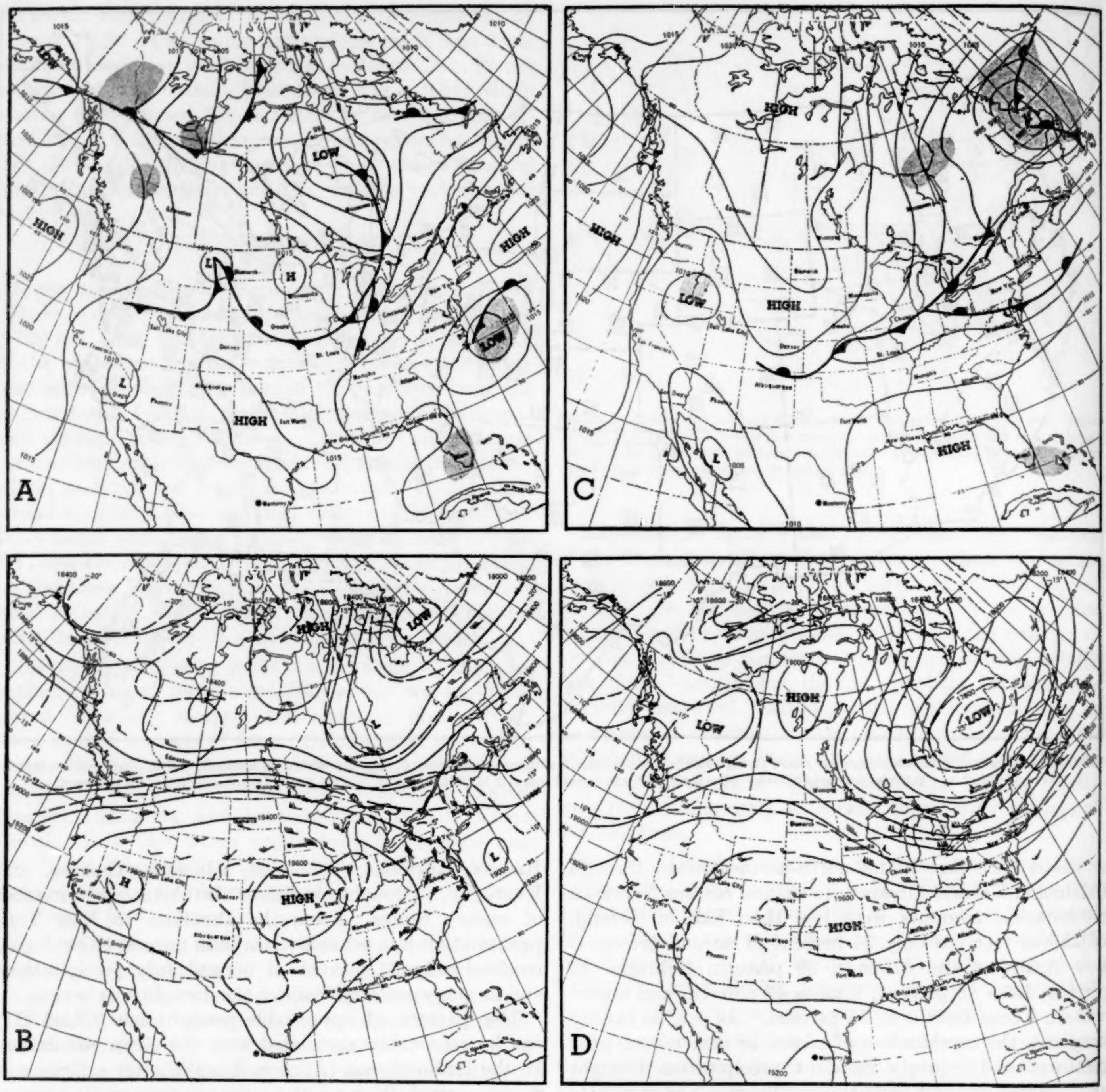


FIGURE 7.—(A) Sea level synoptic map, 1:30 p. m. EST, July 12, 1954. Extreme temperatures occurred over central United States in advance of the cold front. (B) 500-mb. map 10 p. m. EST, July 12, 1954. The air over Missouri was turning anticyclonically and trajectories show advection from the west along northern edge of the High. Note well-marked jet to north. (C) Sea level synoptic map, 1:30 p. m. EST, July 14, 1954. Note similarity to frontal trough of the 12th over central United States but contrast in gigantic "warm sector" across the East Central States. New maximum absolute temperatures were established over a wide area preceding the cold front passage. (D) 500-mb. map. 10 p. m. EST, July 14, 1954. Ridge now extended eastward much more prominently than on the 12th. Westerly winds aloft occurred almost all the way to the east coast and the jet to the north showed winds of 70 knots or better at this level.

to northwestern Florida also received above normal precipitation. The latter was due to a small tropical disturbance which affected Southern Louisiana at the month's end (Chart X) as the upper level anticyclone split in two.

In the far Northwest, coastal Washington and Oregon had above normal precipitation under the cyclonic southwesterly flow and below normal heights at 700 mb. The moisture track extended eastward through northern Idaho and western Montana and was generally associated with the passage of trailing fronts. Elsewhere the arid sections of California, eastern Oregon, and southern Idaho received little or no precipitation.

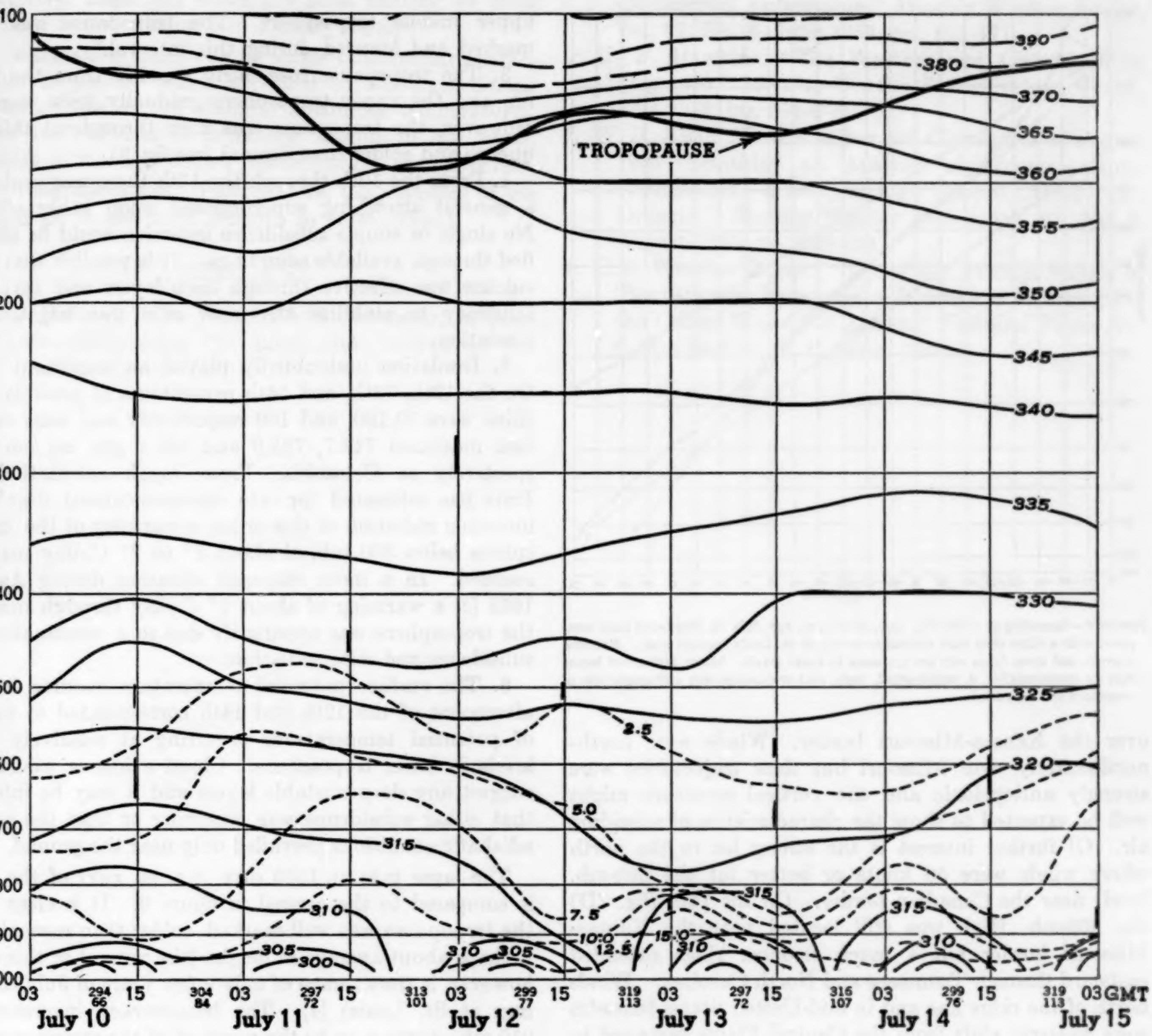


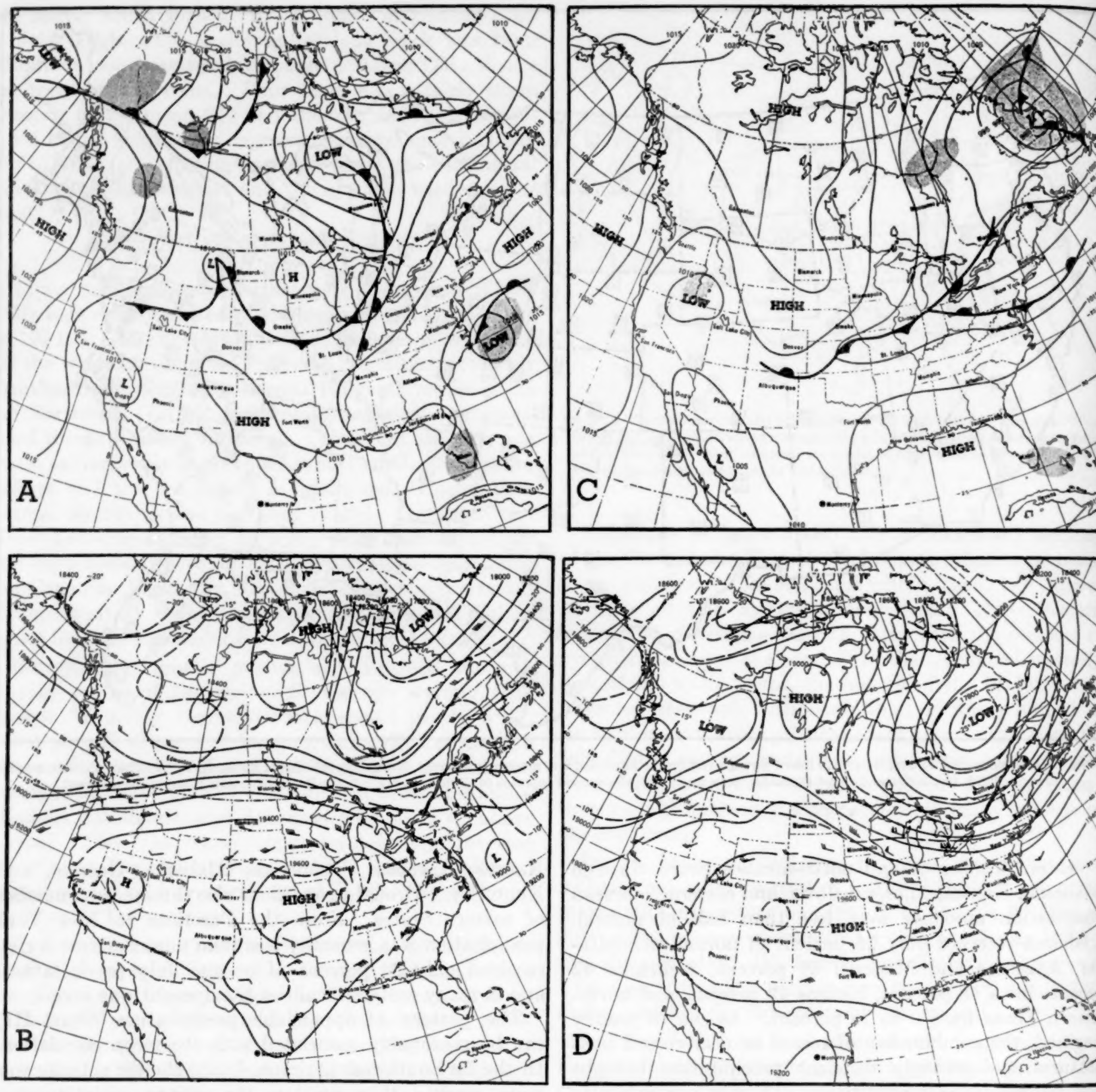
FIGURE 8.—Time section of soundings at Columbia, Mo., July 10–15, 1954. Vertical (pressure) scale is logarithmic. Potential temperatures are indicated by solid lines where analyzed for every 5° C. and by dashed lines where analyzed for every 10°. Lines of equal mixing ratio are drawn for every 2.5 gm./kg. of dry air. Approximately dry adiabatic lapse rates are indicated by solid vertical lines adjacent to the portion of sounding where such conditions prevailed. Maximum and minimum surface temperatures are given in ° F. and in terms of potential temperature in ° C.; they are interpolated in the time scale by estimating time of occurrence. Note frontal surface at 820 mb. on July 13, 0300 GMT.

THE HOTTEST PERIOD

The establishment of so many new absolute temperature records during July quite naturally led to some curiosity as to the structure of the atmosphere accompanying their occurrence. What follows is a brief examination pertaining chiefly to Columbia, Mo., from July 10 to 14. New records were set on the 12th (113° at Columbia and Springfield, Mo.) and on the 14th (113° at Columbia and 115° at St. Louis).

Figure 7A shows the sea level synoptic situation at 1:30 p. m. EST, July 12. The frontal trough extending from Michigan southwestward had formed east of the Continental Divide and had been located in the eastern Dakotas on the 11th. The small Low in eastern Montana (fig. 7A) moved eastward to the Dakotas on the 13th and by the 14th this trough was similarly extending from southern Michigan southwestward to northeastern Kansas (fig. 7C). In both cases the extreme temperatures occurred in the general westerly drift which preceded the cold front passage. This flow, while by no means strong, probably assured some adiabatic warming in lower levels through downslope motion but the effect was not marked.

The 500-mb. map for 10 p. m. EST of the 12th (fig. 7B) shows the strong upper level anticyclone centered



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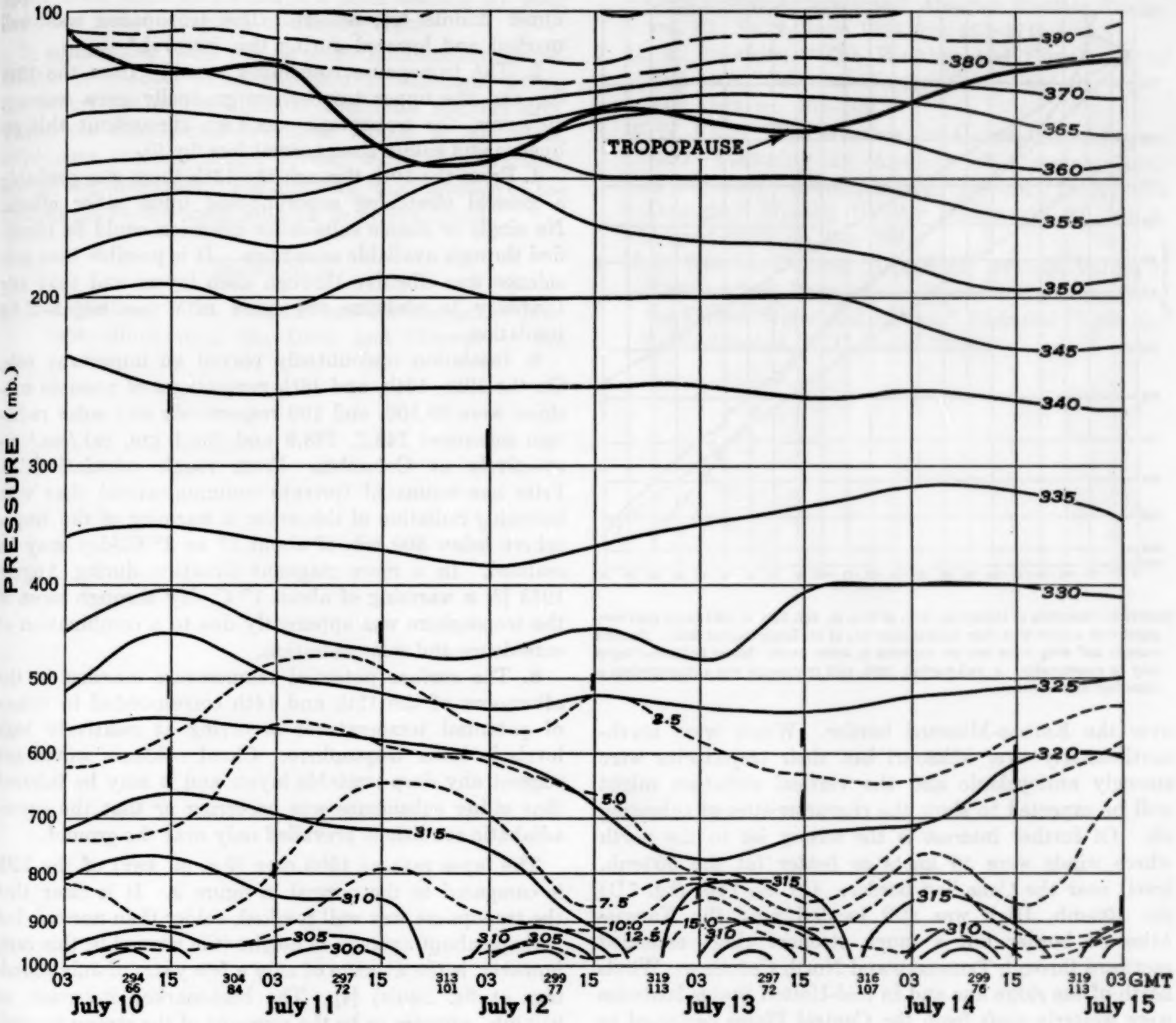

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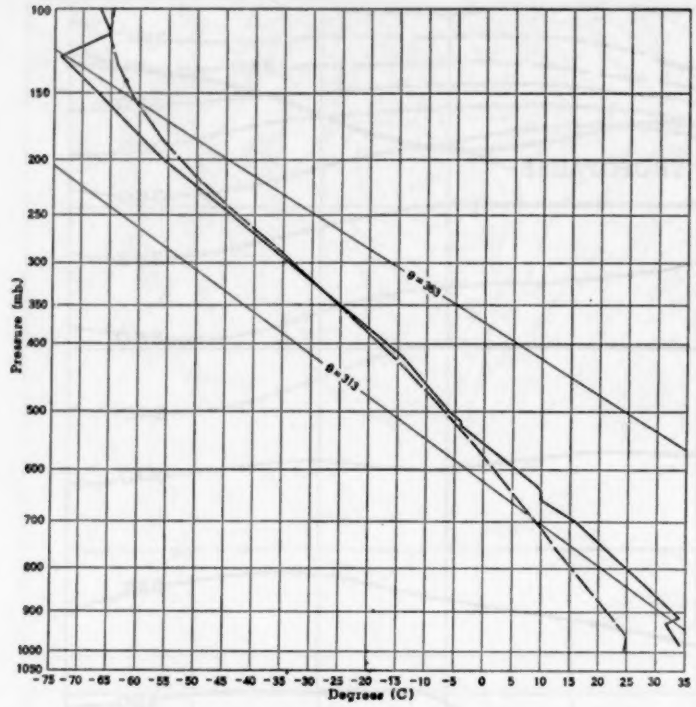

FIGURE 9.—Sounding at Columbia, Mo., at 10 a. m. EST, July 12, 1954 (solid line) compared with a short term July normal sounding at St. Louis (dashed line). Extreme warmth and steep lapse rate are apparent in lower levels. Minor isothermal layers may be questionable. A well-marked, high, cold tropopause was a characteristic of soundings for this period.

over the Kansas-Missouri border. Winds were north-northeasterly over Missouri but their trajectories were strongly anticyclonic and the vertical structure might well be expected to show the characteristics of subsiding air. Of further interest is the strong jet to the north where winds were 50 knots or better (at the 500-mb. level) near the Canadian border. On the 14th (fig. 7D) the 500-mb. High was still located near the Kansas-Missouri border but a much stronger ridge extended eastward through Tennessee and North Carolina. Winds north of the ridge line and in mid-United States latitudes were westerly aloft from the Central Plains eastward to the east coast. The jet was again well marked with winds of 70 knots or better over the lower Lakes at 500 mb. Absolute maximum temperature records were set from Tulsa, Okla., as far east as Greensboro, N. C., in one gigantic "warm sector."

Figure 8 is the time section of the soundings for Columbia, Mo., from July 10 to 15. The following general observations are possible.

1. The lower troposphere warmed from the 10th to the 12th. This warming was accompanied initially by increasing values of the mixing ratio and seemed due partly at least to warm air advection at lower levels as cool air gave way to warm.

2. During this same period cooling was evident above 200 mb. with some evidence of vertical stretching in the upper middle troposphere. The tropopause was well marked and lowered during this interval.[2]

3. The tropopause rose fairly steadily from the 12th on, and the upper troposphere gradually grew warmer. However, the tropopause was high throughout this sequence and colder than normal (see fig. 9).

4. From the 10th through the 13th there was probably a general stretching superimposed upon other effects. No single or simple subsidence inversion could be identified through available soundings. It is possible that subsidence was effective through deep layers and that any tendency to stabilize the lapse rate was negated by insolation.

5. Insolation undoubtedly played an important role. On the 12th, 13th, and 14th percentages of possible sunshine were 99,100, and 100 respectively and solar radiation measured 743.7, 738.9 and 736.1 gm. cal./cm.^{2} respectively at Columbia. From rough calculations S. Fritz has estimated (private communication) that with incoming radiation of this order, a warming of the troposphere below 500 mb. of about 1° to 2° C./day may be realized. In a more stagnant situation during August 1953 [3] a warming of about 1° C./day through most of the troposphere was apparently due to a combination of subsidence and solar radiation.

6. The surface potential temperature maxima in the afternoons of the 12th and 14th corresponded to values of potential temperatures occurring at relatively high levels in lower troposphere. Cloud evidence would not suggest any deep unstable layers and it may be inferred that either subsidence was occurring or that the superadiabatic conditions prevailed only near the ground.

The lapse rate at 1500 GMT (9 a. m. EST) of the 12th is compared to the normal in figure 9. It is clear that the tropopause was well marked, colder than normal, but perhaps about average in height (the normal in this case, however, is the average of only a few years of July soundings at St. Louis) [4]. The best-marked inversion, at 910 mb., appears to be the remnant of the strong ground-radiation inversion. The other two stable zones at 650 and 520 mb. cannot be traced through the series of soundings and also appear higher than might be expected of subsidence inversions. Extreme warmth of the sounding on the 12th (lower levels) is apparent by its displacement from normal.

The absence of a well-marked, persistent subsidence inversion in a somewhat similar situation has been noted by Klein in a previous article [3] and substantiated by a more thorough investigation by Fritz (private communication). It seems likely that these inversions persist only when a sea level anticyclone is present under the

[2] In these soundings the tropopause was not only the coldest temperature of the soundings but also the point where the lapse rates changed from near adiabatic to isothermal or (more frequently) to increasing temperatures with height.

upper level High and when low level heating by solar radiation is not adequate to destroy them.

In summation there was no single outstanding characteristic or process which appeared to dominate during the occurrence of the absolute maximum temperatures. There was evidence of downslope motion in low levels, subsidence through deeper levels, warm air advection, and strong insolation. Furthermore, the influence of the marked jet to the north remains to be evaluated.

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upper-level High and when low-level heating by solar [illegible] a cutoff [illegible] destroyed.

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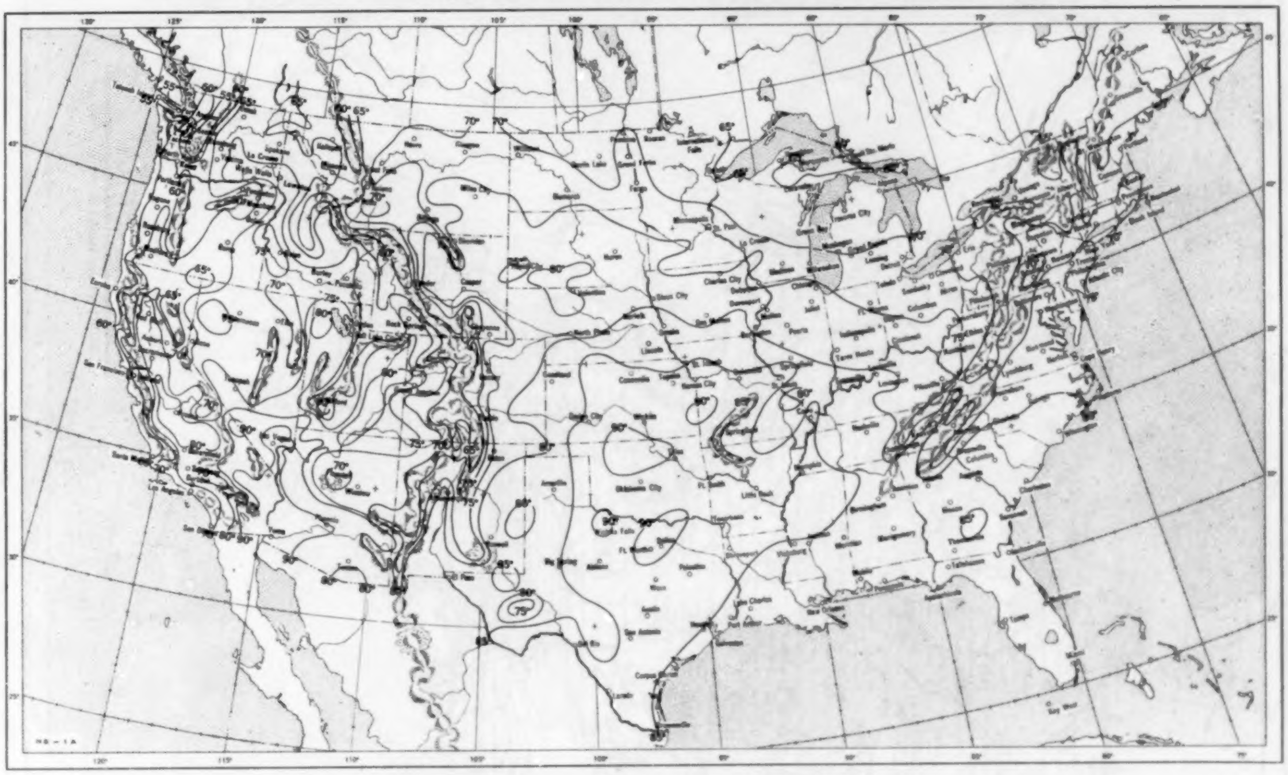
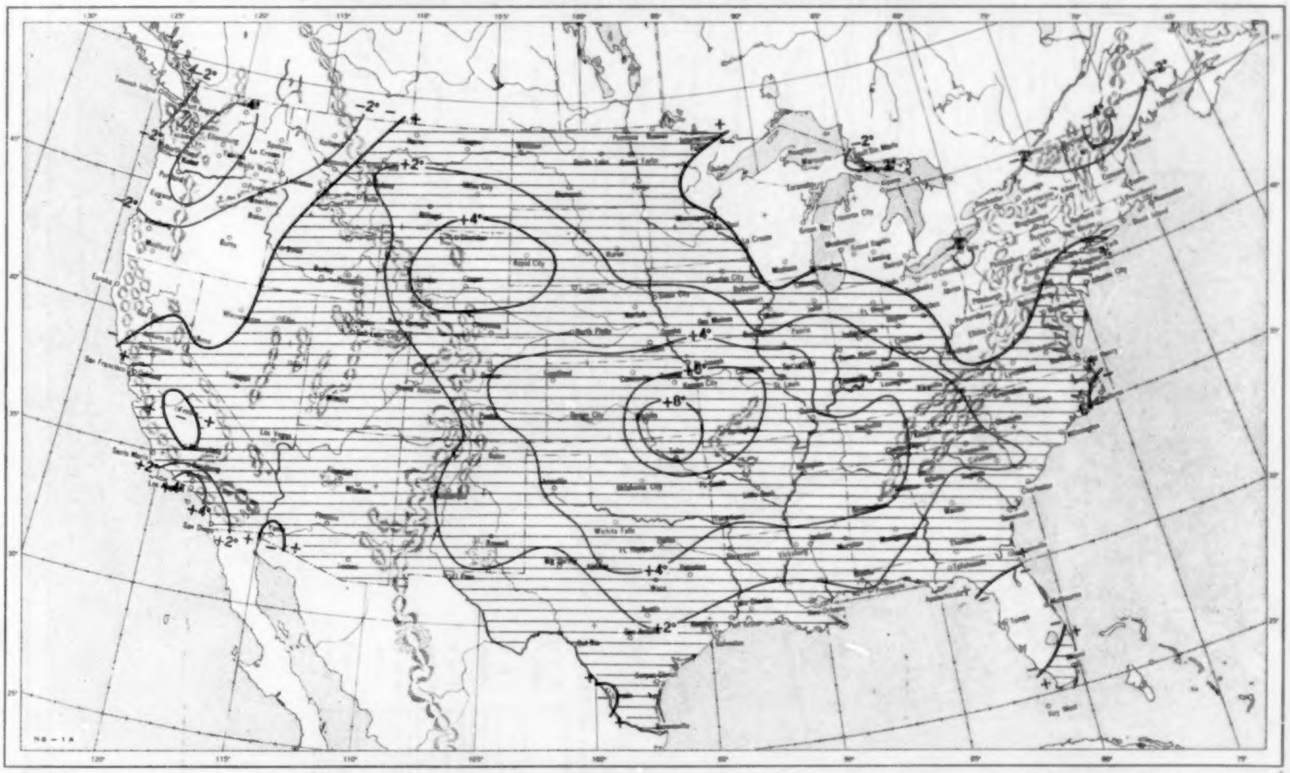
REFERENCES

1. [illegible] "The Weather and Circulation [illegible] [illegible] the [illegible] and [illegible]

Chart I. A. Average Temperature (°F.) at Surface, July 1954.

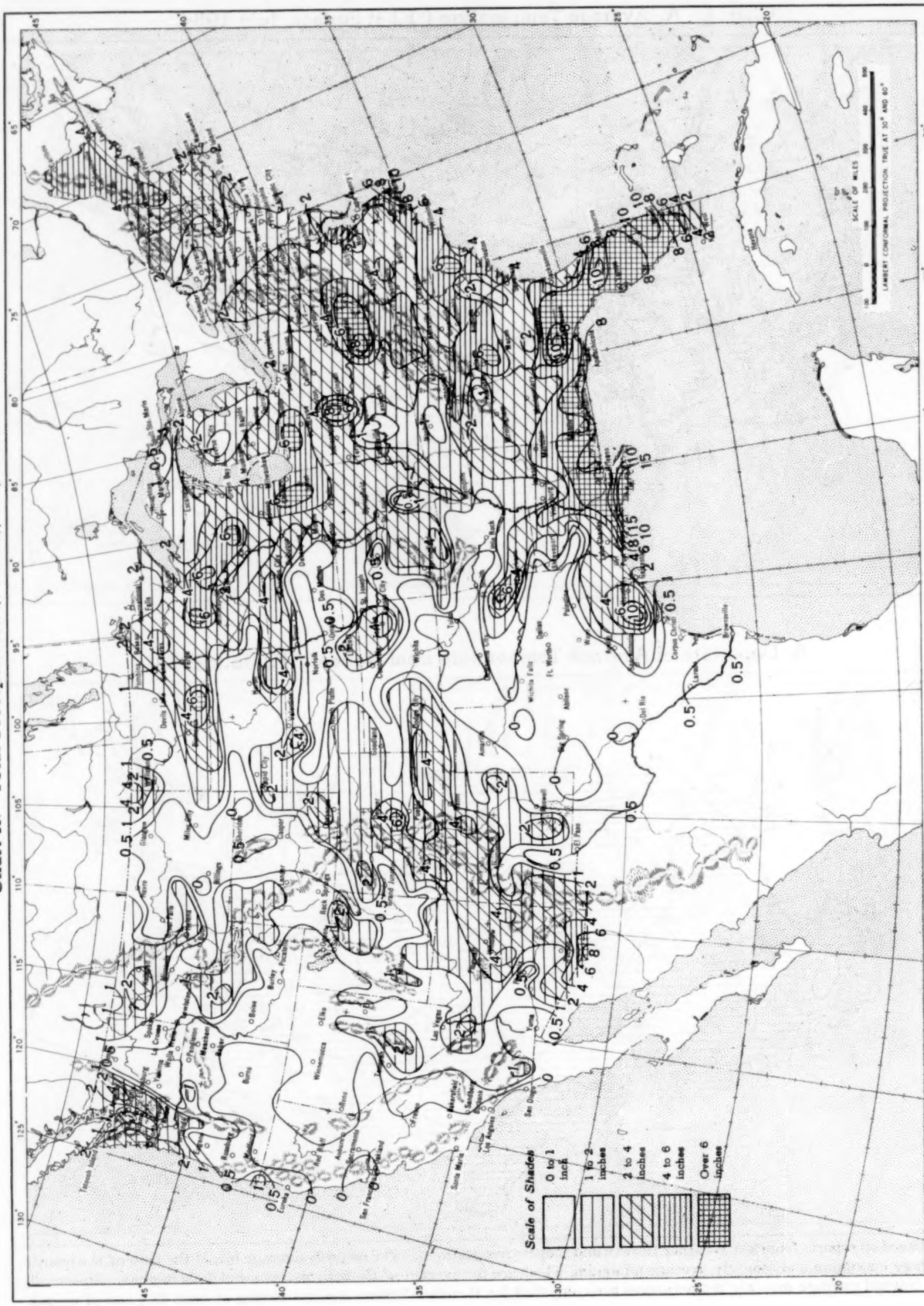


B. Departure of Average Temperature from Normal (°F.), July 1954.



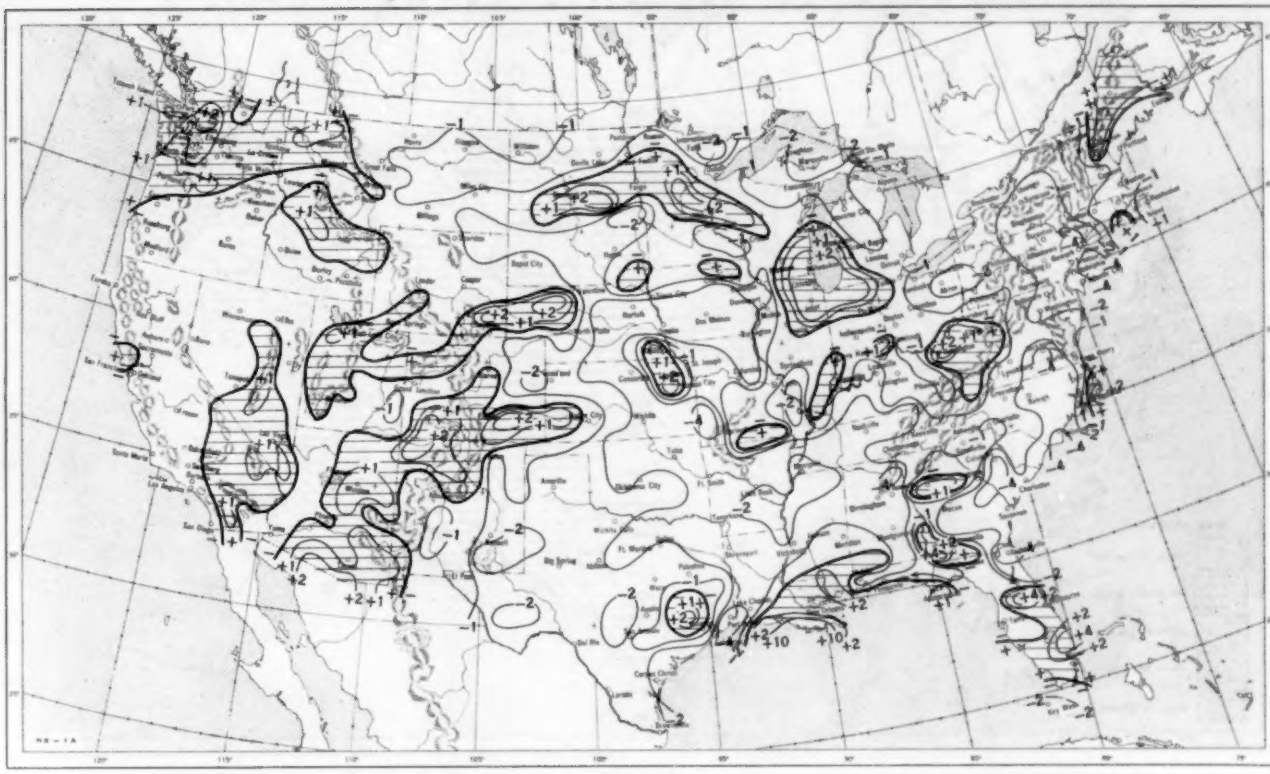
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), July 1954.

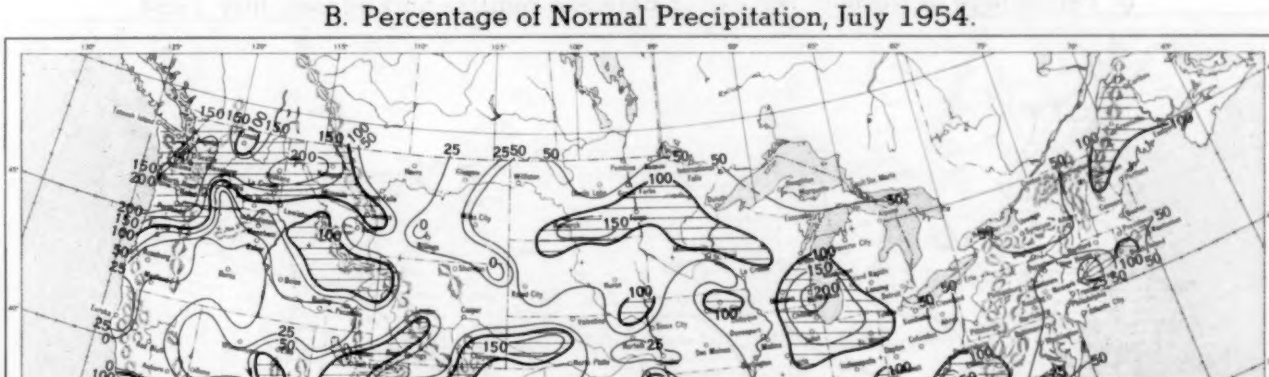


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), July 1954.

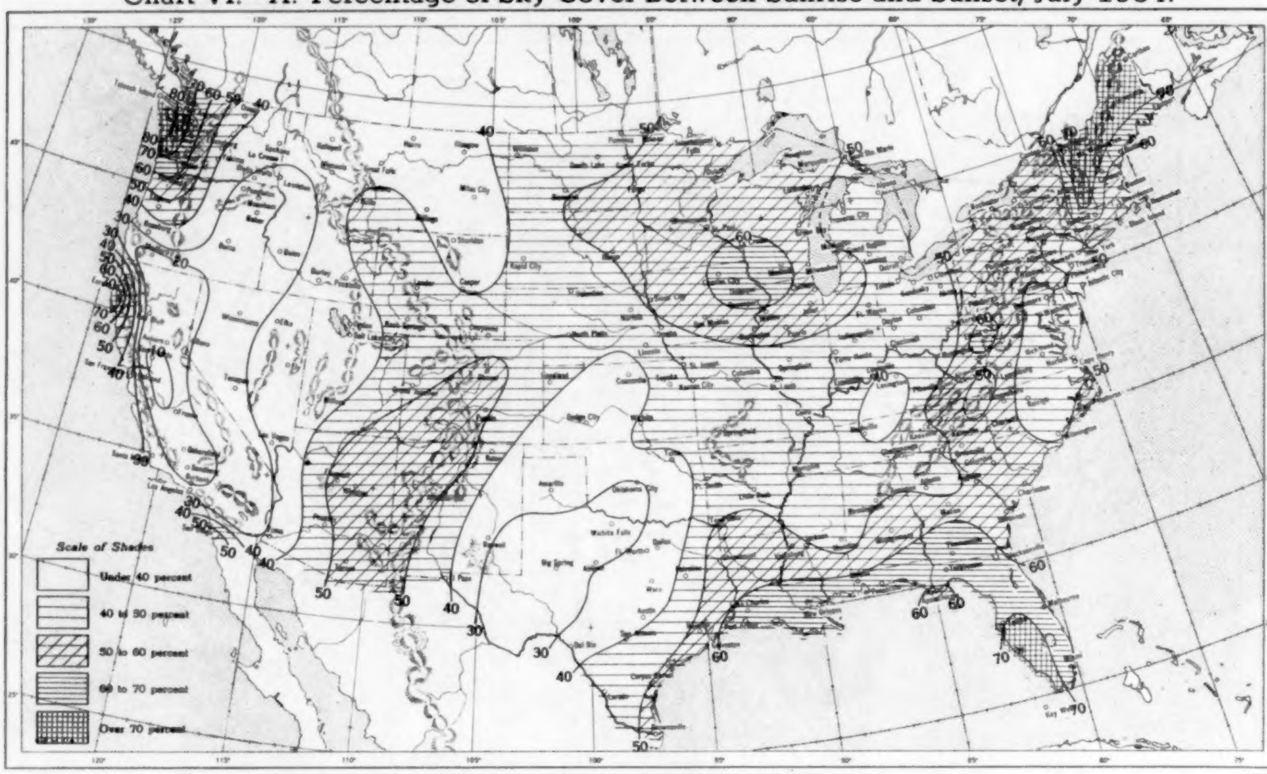


B. Percentage of Normal Precipitation, July 1954.

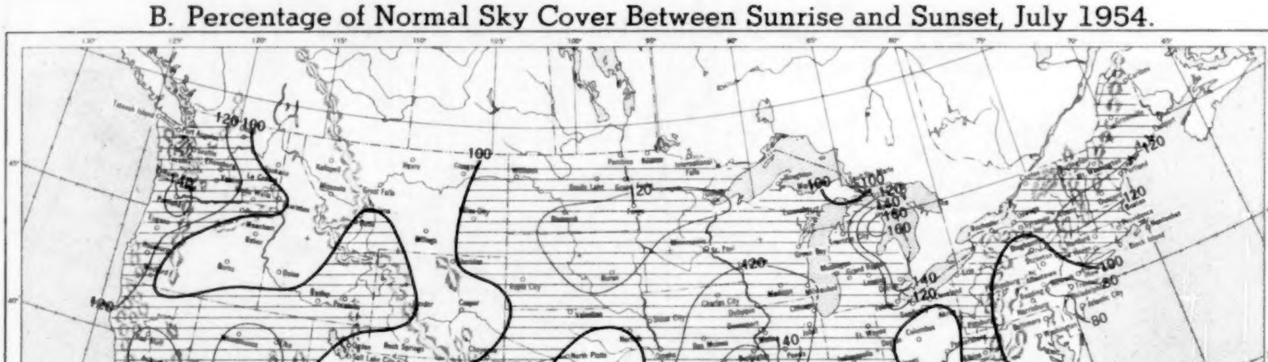


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, July 1954.

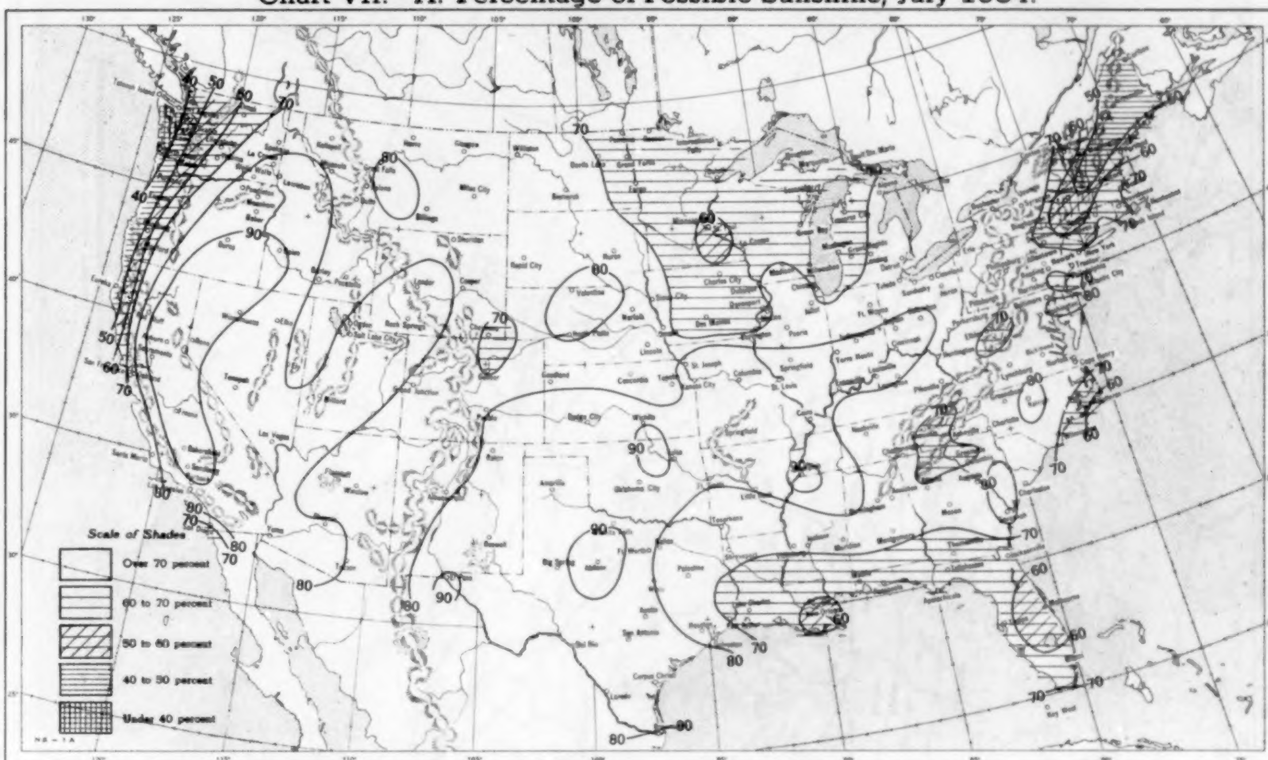


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, July 1954.

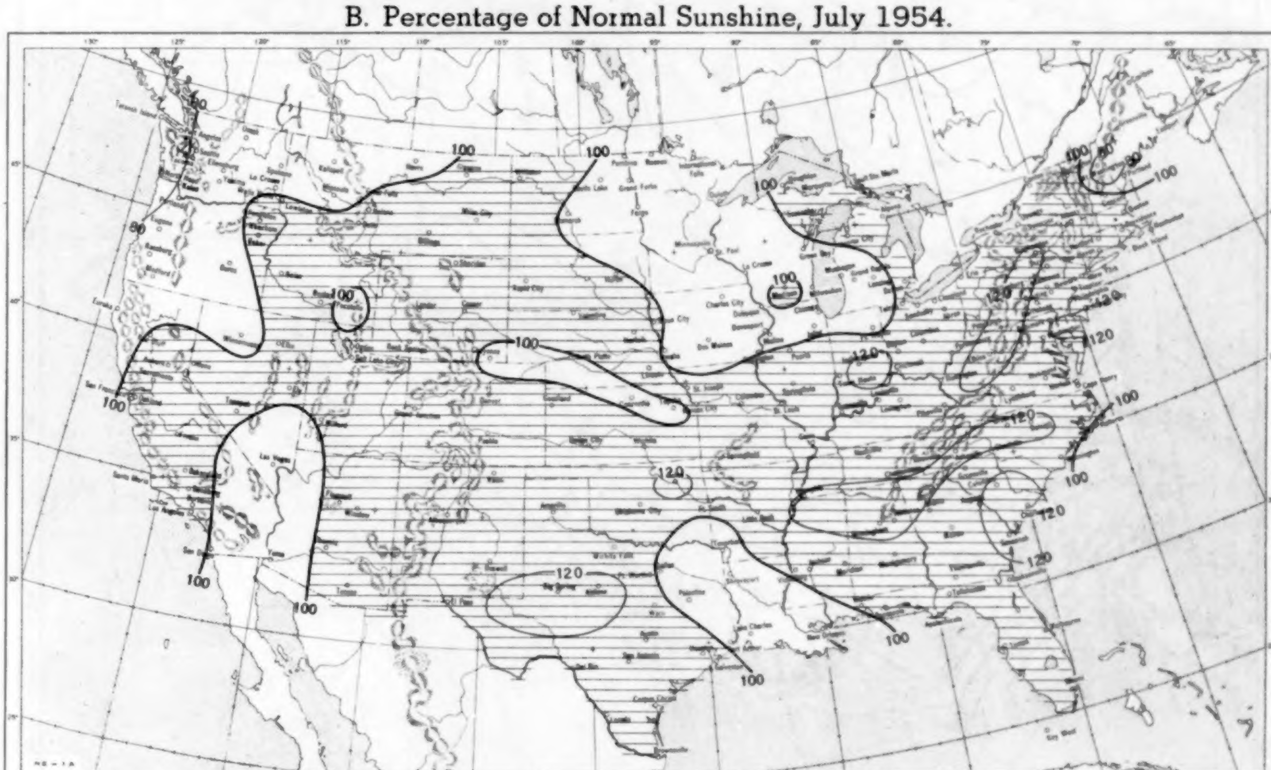


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, July 1954.



B. Percentage of Normal Sunshine, July 1954.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, July 1954. Inset: Percentage of Normal Average Daily Solar Radiation, July 1954.

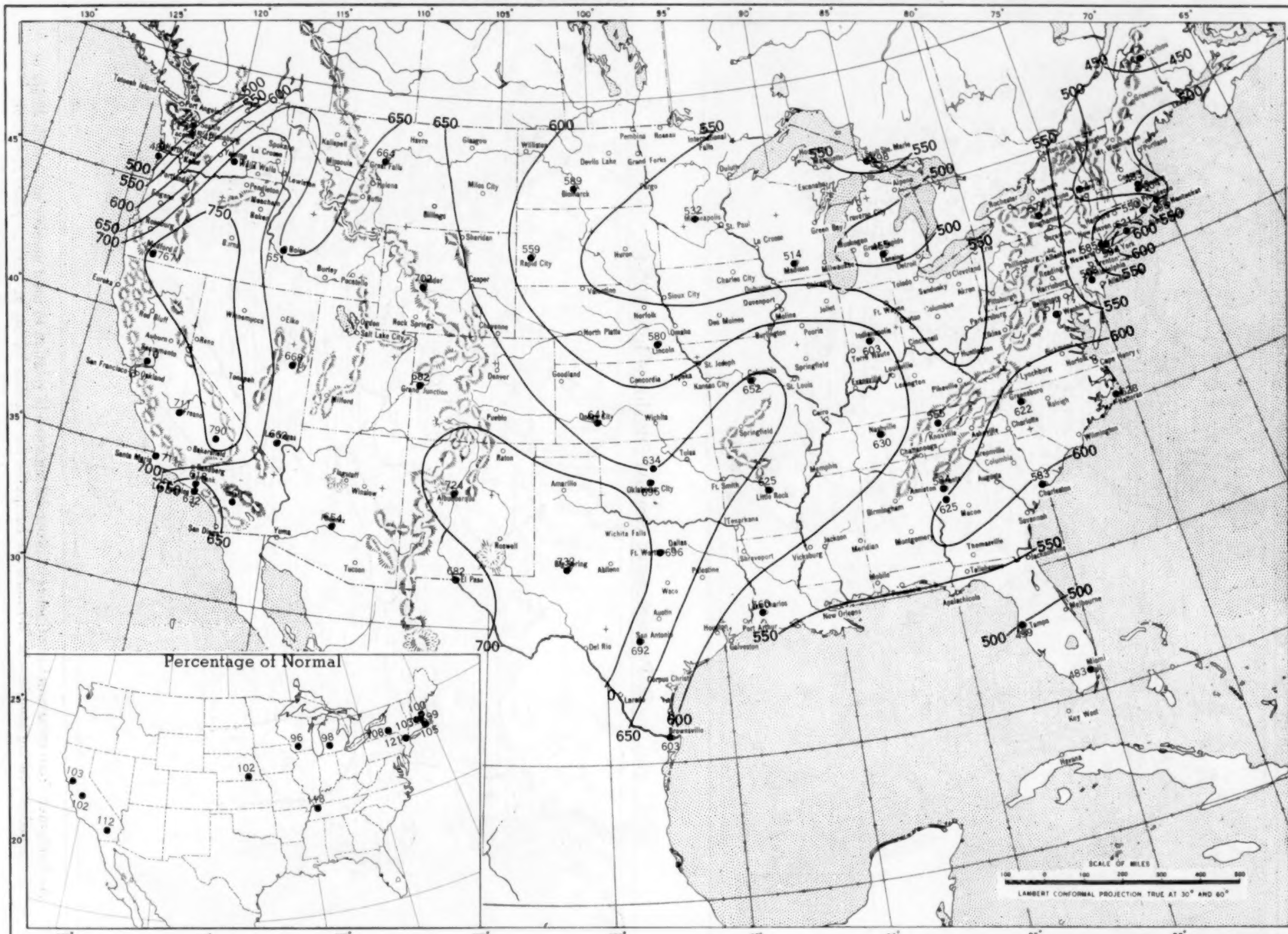
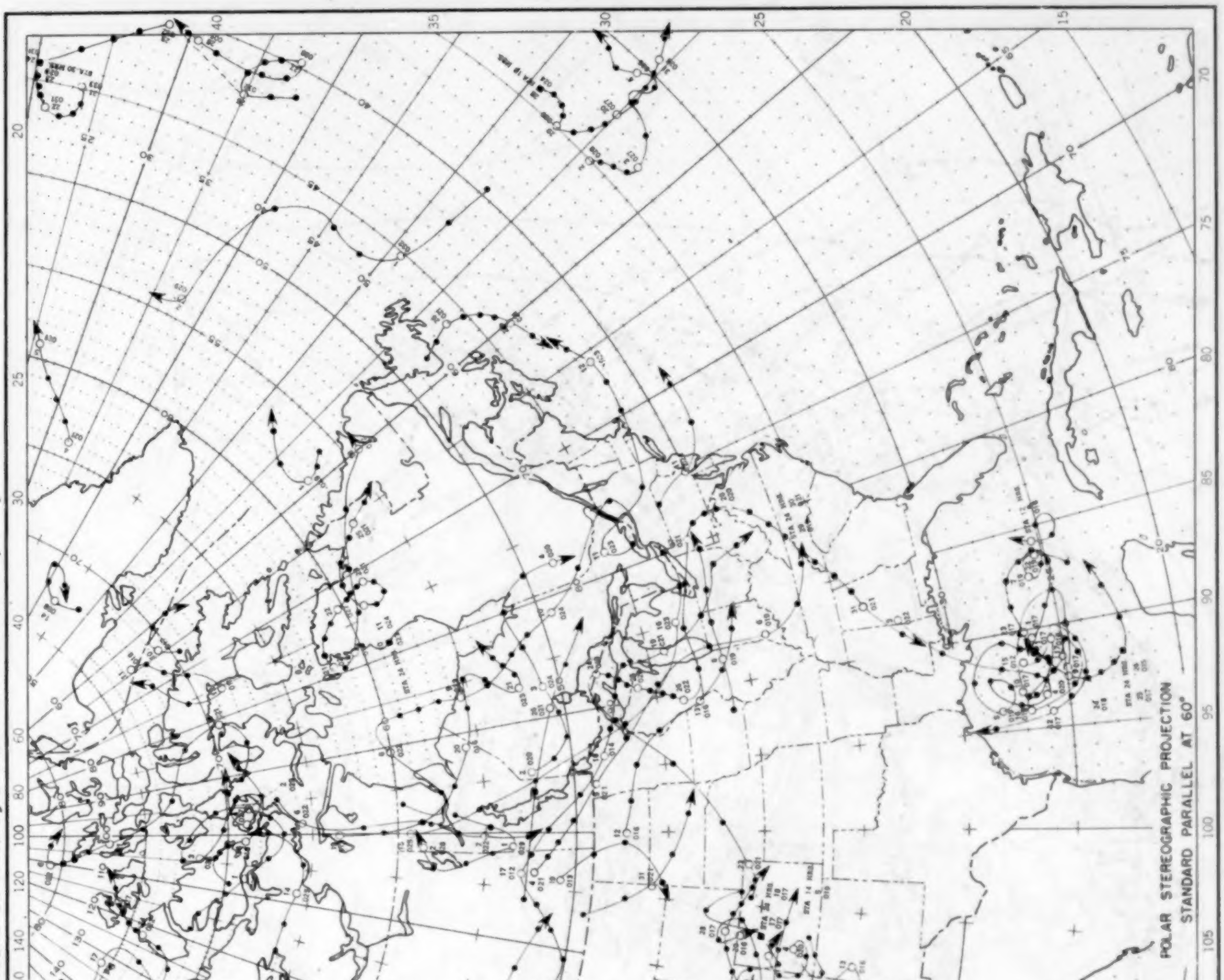


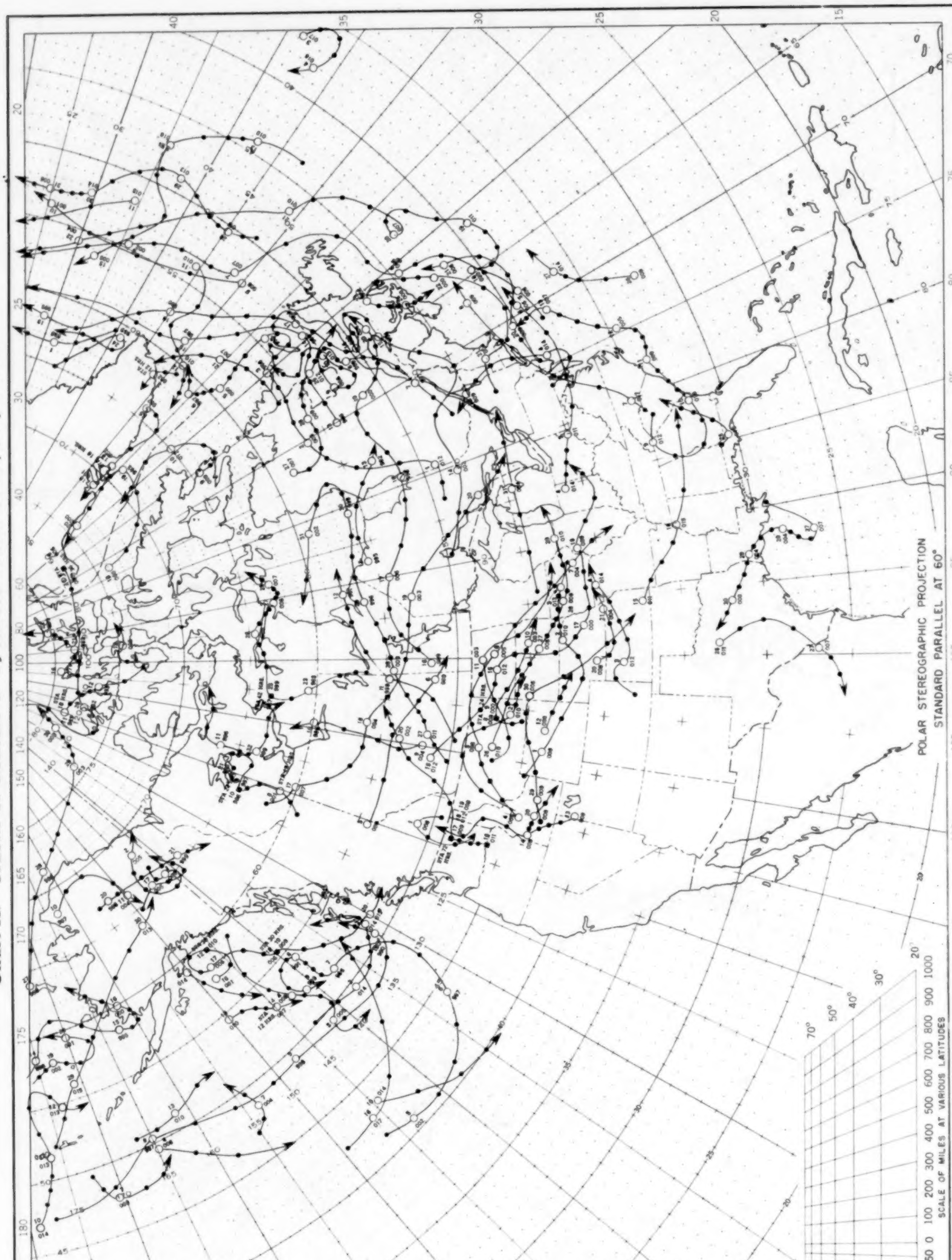
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, July 1954.



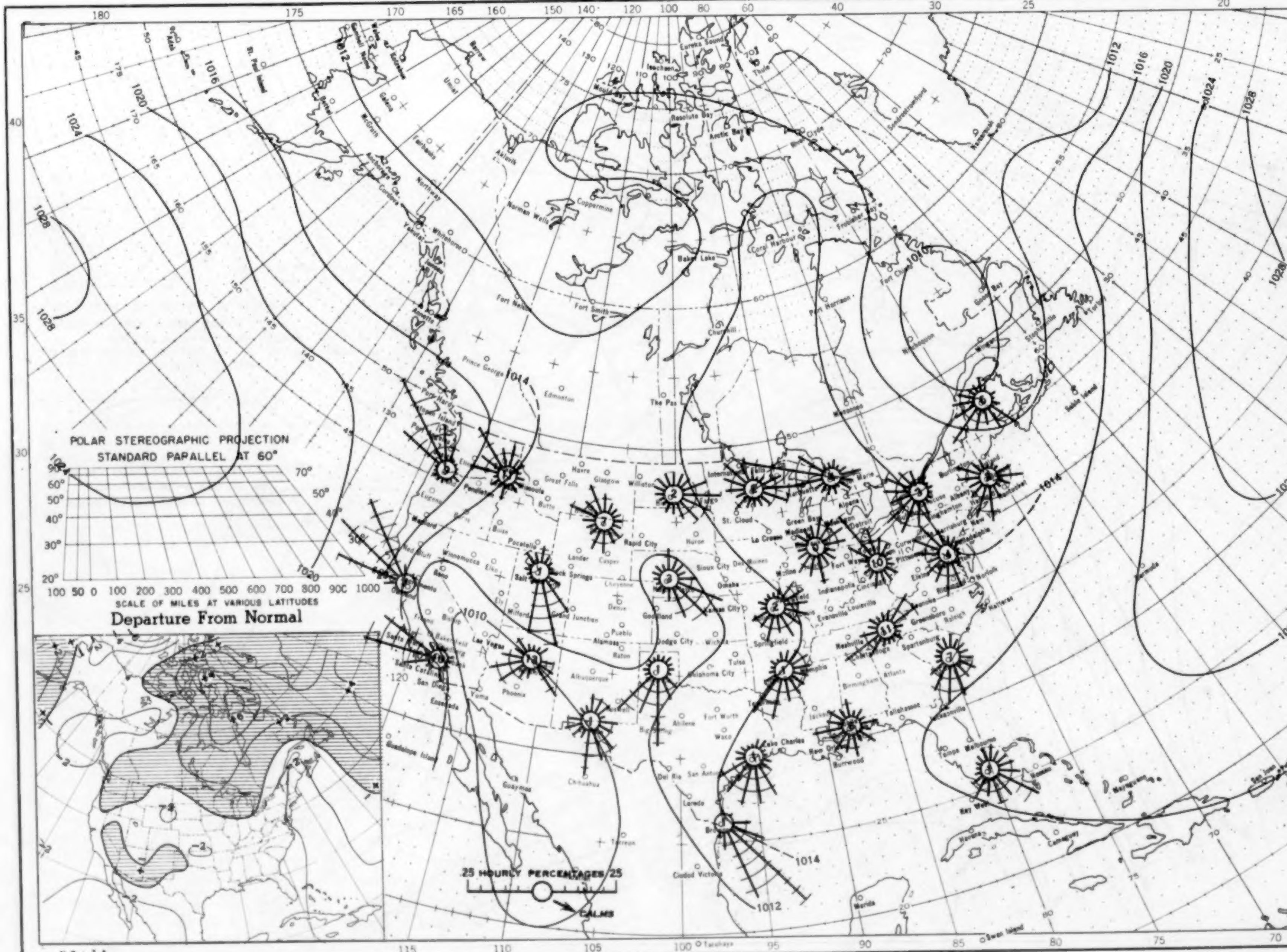
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, July 1954.



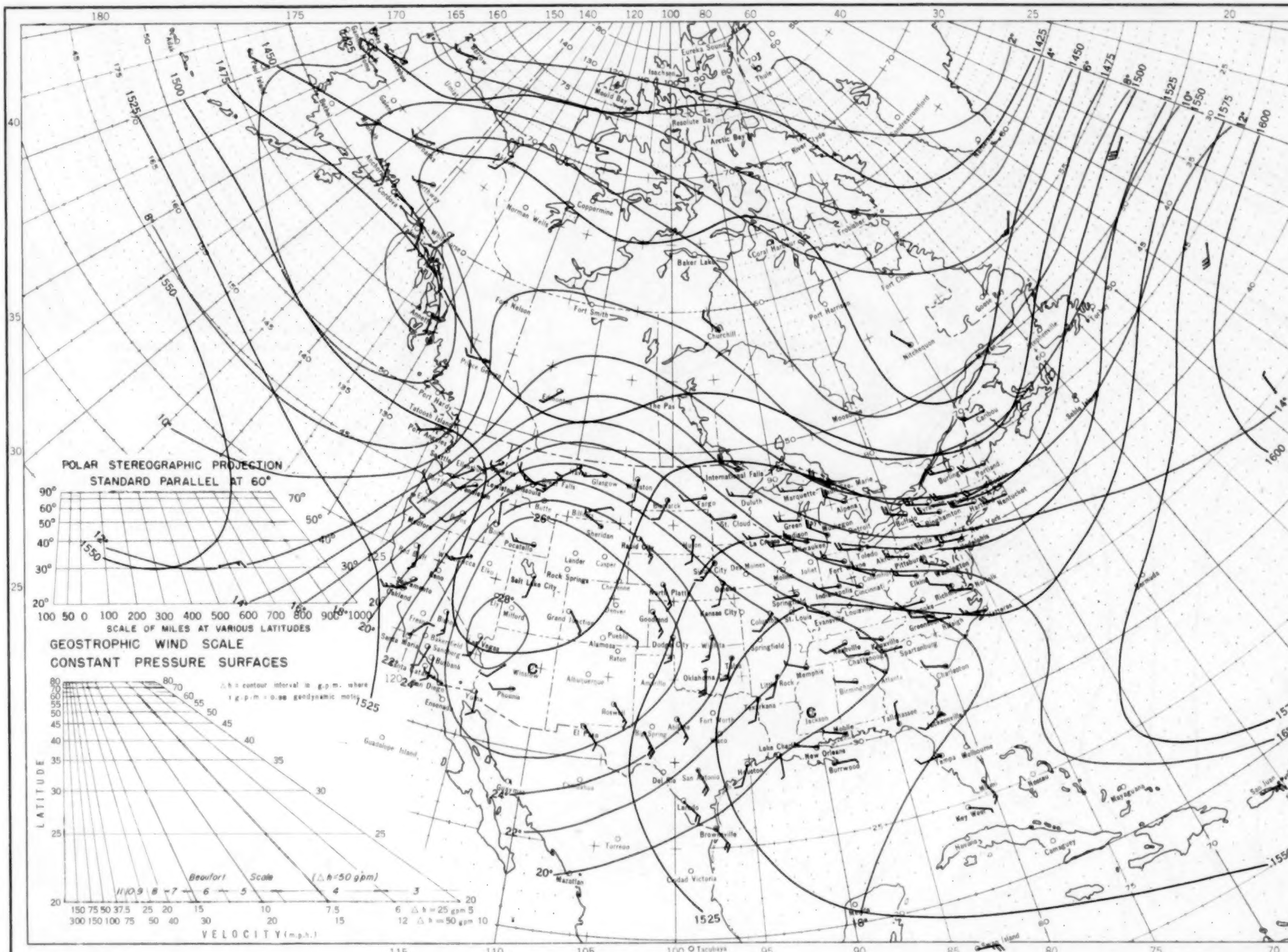
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, July 1954. Inset: Departure of Average Pressure (mb.) from Normal, July 1954.



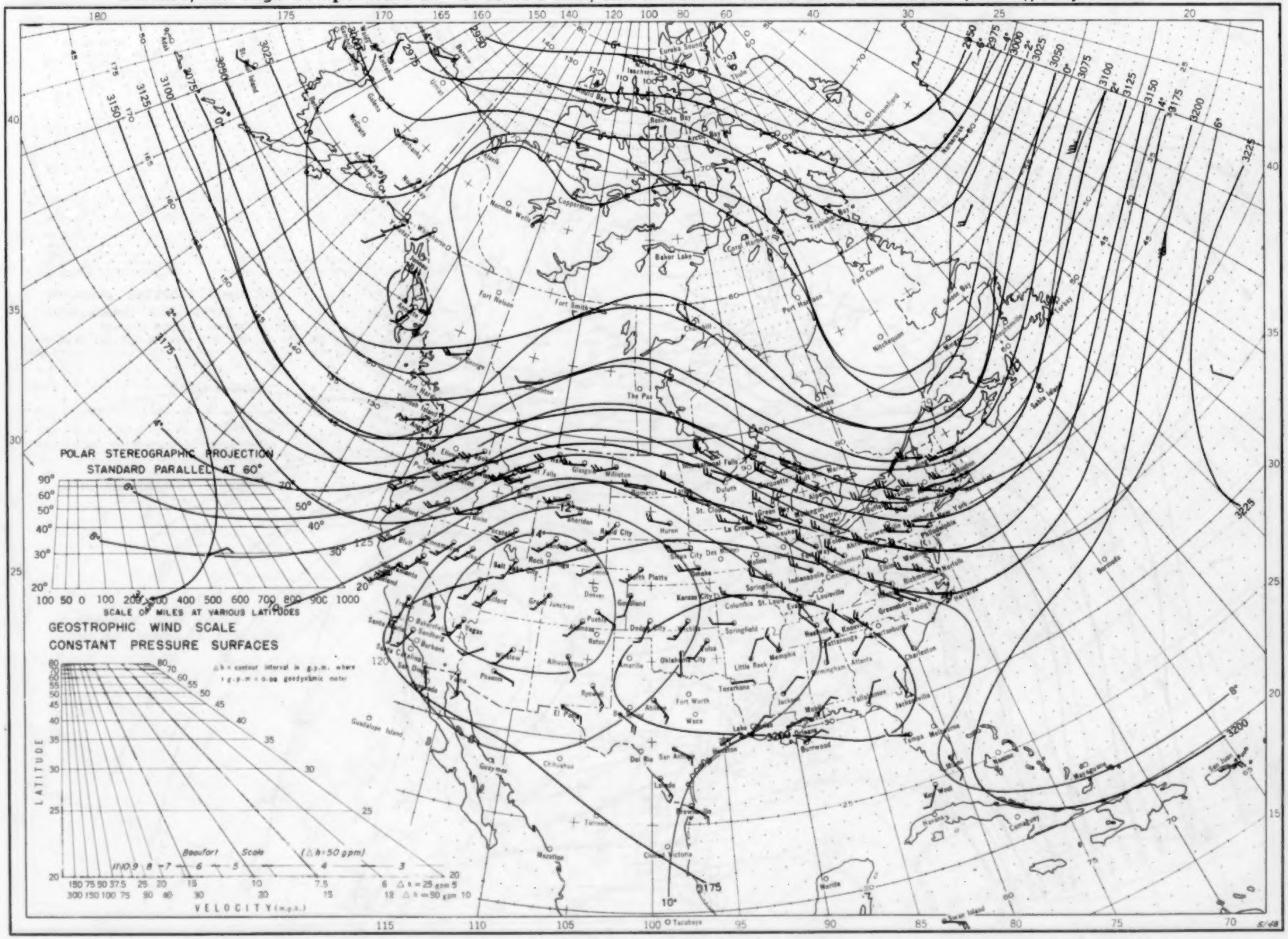
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), July 1954.



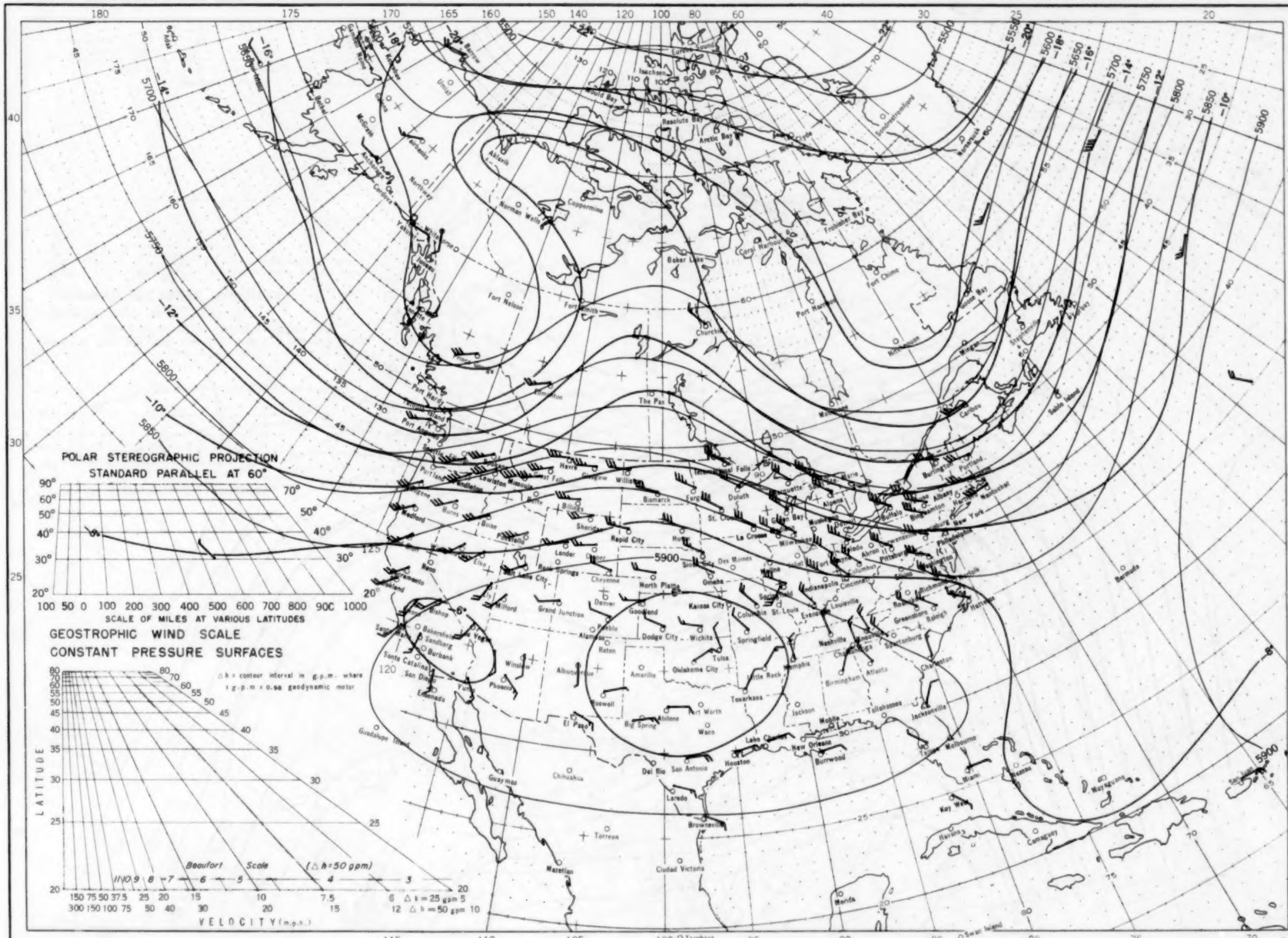
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), July 1954.



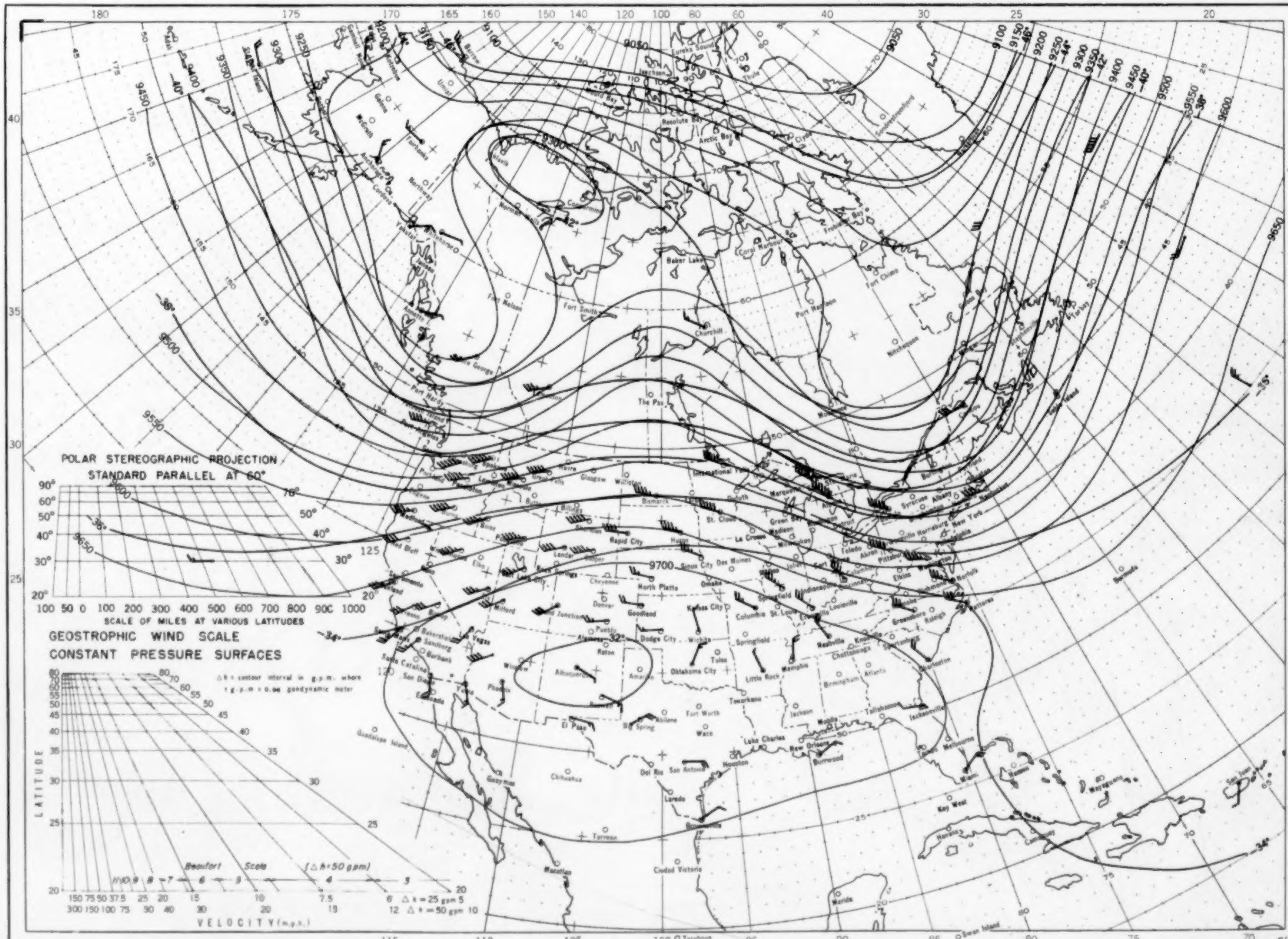
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), July 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.: those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), July 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.